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AD-A032 536

A METHODOLOGY FOR SUBJECTIVE ASSESSMENT OF PROBABILITY DISTRIBUTIONS

AIR FORCE INSTITUTE OF TECHNOLOGY
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

SEPTEMBER 1976

UNITED STATES AIR FORCE

AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

A METHODOLOGY FOR SUBJECTIVE ASSESSMENT OF PROBABILITY DISTRIBUTIONS

Anthony S. Grayson, Captain, USAF
Harold J. Lanclos, Captain, USAF

SLSR 13-76B

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SLSR# 13-76B	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A METHODOLOGY FOR SUBJECTIVE ASSESSMENT OF PROBABILITY DISTRIBUTIONS		5. TYPE OF REPORT & PERIOD COVERED Master's thesis
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Anthony S. Grayson, Captain, USAF Harold J. Lanclos, Captain, USAF		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Graduate Education Division School of Systems and Logistics Air Force Institute of Technology,WPAFB,Oh		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Department of Research and Communicative Studies (SLGR) AFIT/SLGR, WPAFB, OH 45433		12. REPORT DATE September 1976
		13. NUMBER OF PAGES 157
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

APPROVED FOR PUBLIC RELEASE AFR 190-17.

JERRAL F. GUESS, CAPT, USAF
Director of Information

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Probability
Uncertainty Analysis
Risk Analysis
Source Selection
Probability Assessment

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Thesis Chairman: Martin D. Martin, Lieutenant Colonel, USAF

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

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In the initial stages of development of a weapon system it is impossible to know with complete certainty what the final outcome of the weapon system will be in terms of completion time, cost, and performance. Conversely, decision makers and technical experts are not completely ignorant of the possible outcomes. Therefore, a language is needed which expresses the degree of belief that certain outcomes will occur. Subjective probability is such a language. The authors describe the following techniques for assessing subjective probability: Choice-Between-Gambles, Standard Lottery, Modified Churchman-Ackoff, Delphi, DeGroot Consensus, and Direct Estimation. Using content analysis, the authors evaluate each of the subjective probability techniques with respect to each of the following criteria: ease of application, adaptability and flexibility, reliability and validity, time, removal of bias, and miscellaneous. Based upon the content analysis, the Standard Lottery technique is the technique which best assesses the magnitude of uncertainty present in a given weapon system's development effort. The authors state that the results of the research are inconclusive, since the sample size for each subjective probability technique, both in number of sources and in the amount of material within each source, was highly variable.

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This thesis, written by

Captain Anthony S. Grayson

Captain Harold J. Lanclos

has been accepted by the undersigned on behalf of the faculty of the School of Systems and Logistics in partial fulfillment of the requirements for the degrees of

MASTER OF SCIENCE IN LOGISTICS MANAGEMENT (PROCUREMENT MAJOR)

MASTER OF SCIENCE IN LOGISTICS MANAGEMENT

DATE: 7 September 1976

Martin D. Martin

COMMITTEE CHAIRMAN

SLSR 13-76B

A METHODOLOGY FOR SUBJECTIVE ASSESSMENT OF PROBABILITY DISTRIBUTIONS

A Thesis

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Logistics Management

By

Anthony S. Grayson, BA
Captain, USAF

Harold J. Lanclos, BS
Captain, USAF

September 1976

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ACKNOWLEDGMENTS

We wish to express our appreciation to those who were most instrumental in making this thesis possible. They are:

Lt Col Martin D. Martin, our thesis advisor, who gave guidance and offered constructive criticism of our work;

Mr. Al Greenhorn, our reader, who aided us with his comments and suggestions; and,

Finally, our wives, Darlene and Judy, who encouraged us greatly in our studies, spent many hours typing the drafts and the thesis, and willingly accepted the major share of family responsibilities during the school year.

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Chapter 1

INTRODUCTION

In the initial stage of development of a weapon system it is impossible to know with complete certainty what the final outcome of the weapon system will be in terms of completion time, cost, and performance. Conversely, decision makers and technical experts are not completely ignorant of the possible outcomes. Therefore, a language is needed which expresses the degree of belief that certain outcomes will occur. Subjective probability is such a language.

This chapter presents the statement of the research problem, the justification for this research, the scope and objective of the research, and the research question.

STATEMENT OF THE PROBLEM

The problem is that a methodology does not exist for assessing the magnitude of uncertainties in the weapons acquisition process. The uncertainties surrounding the weapons acquisition process have had their most telling effect on the ability of military planners to estimate the cost of weapon systems, the time required for system development, and the capability of achieving specified performance characteristics. Uncertainties in the

parameters of schedule and performance affect the area of costs most dramatically (61:2). The significance of these weapon system uncertainties is apparent when major weapon system costs are studied.

A research study by Peck and Scherer of twelve programs of the late 1950's revealed an average weapon system development cost growth of 220 percent when compared to estimated costs (70:429). A later study by Marschak of 22 weapon system development programs in the 1960's showed an average cost growth over estimated costs of 226 percent (5:2). A General Accounting Office study in 1972 of 77 major weapon systems revealed that new cost estimates were running 28.7 billion dollars above the original cost estimates, representing an average expense increase of 31 percent from original cost estimates (38:2).

R. L. Perry compared weapon development programs of the 1950's to those of the 1960's, and demonstrated that cost estimates for the 1960's were about 25 percent less optimistic than those for the 1950's (100:1-2). A follow-up study by Harman, using improved data over Perry's study, produced different results. Harman concluded there was no indication of a significant difference between the 1950's and the 1960's in the ability of the weapon system acquisition process to estimate costs or to avoid actual cost overruns (40:38). Thus, there was no improvement between the 1950's and the 1960's in the capability of cost estimation techniques to reduce the uncertainty in the

weapon system acquisition process with better cost information.

JUSTIFICATION

Uncertainty of Future Costs

The following comments, made by the Blue Ribbon Defense Panel, indicated the types of problems encountered when cost estimates were used without regard to the uncertainties surrounding the estimate:

> Cost estimating for development programs has apparently been too widely credited in the Defense Department, in industry, in the Congress, and by the Public with a potential for accurate prediction which is belied by the inherent technical uncertainties in developments. The precise problems which may be encountered in the process of attempting to convert a technological or scientific theory or experiment into practical, producible application cannot be foreseen with accuracy. It should be axiomatic that one cannot place a price on an unknown; yet . . . the use of precontractual cost estimates as a firm baseline for measuring performance throughout the life of the system, and the shock reaction which is forthcoming when cost overruns are experienced, all evidence an unwarranted degree of confidence in cost estimates [32:83].

The critical factor determining the accuracy of a cost estimate is the degree of uncertainty present at the time the cost estimate is made. Summers, in a study of cost estimates as predictors of actual weapon system cost, stated that "considerations of uncertainty go a long way toward explaining the differences in accuracy of cost estimates [84:7]."

At each stage of a major weapon development and production program, from the conceptual to the deployment

of the finished weapon system, an estimate of cost is a major input in management decision making (35:153; 100:31). Prior to the actual award of the contract, the program manager is primarily concerned with influencing the future cost growth of his program. Four types of cost estimates are available to aid the program manager in this concern: Cost Analysis Improvement Group (CAIG) estimates; Independent Cost Estimates (ICE); "in house" Systems Program Office estimates; and contractor proposal estimates (62:15).

After contract award, the program manager must monitor control systems in order to preclude program cost growth (62:15-16). In making his decisions, the program manager must weigh the prospective value of the end product and its prospective date of completion against an estimate of its cost. It is under conditions of uncertainty that the program manager must evaluate and select among alternative proposals for future courses of action, and attempt to control program cost growth.

J. Ronald Fox, a former Assistant Secretary of the Army for Installations and Logistics, stated that:

> All along the road, from idea to systems-inplace, choices must be made that will significantly affect the ultimate costs of the acquisition process. If the services are to achieve sound financial control of these costs, it is essential that they have sound and reliable estimates of the cost implications of their choices [35:154].

It is not clear, however, that decision makers have accepted the fact that knowledge of the uncertainties associated with predictions of future costs is as vital as

the estimate itself (100:31). To overcome the problems pointed out by the Blue Ribbon Defense Panel, decision makers must also obtain information regarding the uncertainties surrounding cost estimates. If the cost estimate involves an advanced weapon system, it is not sufficient to ask whether the cost estimate is uncertain. As Dienemann puts it:

> It is an inescapable fact that estimates of resource requirements for future systems are beset with uncertainty. The question is not whether uncertainty exists, but rather in determining the magnitude and nature of the uncertainty [29:1].

This uncertainty can be reduced through an analysis of the risks associated with the weapon system acquisition, where risk is considered as:

> . . . the probability that a planned event will not be attained within the prescribed constraints as defined by the cost, schedule, and performance criteria by following a specified course of action [58:6].

Dr. Robert Seamans, then Secretary of the Air Force, emphasized the need for risk analysis in a speech to the Air Force Association in September, 1969:

> Still another significant reason for cost growth in the last few years has been the failure to adequately identify the risks associated with major programs. This should occur early in the project definition phase. Late recognition of significant uncertainties can be disastrously expensive. In the future, we will make a formal risk analysis of each of our programs. We must guard against the combination of optimistic pressures, including our own eagerness to get on with the job [58:2].

Former Deputy Secretary of Defense Packard further stated in a letter to the Secretaries of the Armed Services:

> I would like each of you to focus more attention on this matter and assure that during concept formulations, areas of high technical risk are identified and fully considered; formal risk analysis on each program is made; and summaries on these are made part of the backup material for the program [58:2].

Decision makers would be aided by explicit information describing the magnitude and nature of the uncertainty of cost estimates in two ways. First, the event and probability that the ultimate system cost could differ from the expected cost estimate can be anticipated, evaluated, and used as a control mechanism for system cost growth. Second, with a quantitative measure for the precision of cost estimates, decision makers would be better able to judge--based upon their preferences and attitudes toward risk--alternative courses of action (29:2).

The essence of the preceding discussion of the uncertainty of cost estimates is that future final costs may assume a range of values. The relative likelihood of occurrence of a value within this range is expressed through probability. The probability density function can be either discrete or continuous. A discrete probability density function assigns a probability to each number or estimate within the range of the final cost variable. A continuous probability density function can be thought of as a curve, where the height of the curve indicates the relative probability or likelihood that the event described by the horizontal axis (cost) will occur. The discrete probability density function has a finite number of possible events, while in the continuous probability density function the

entire range of possible values of the variable is represented. The variance is a measure of the dispersion of possible final costs around the expected final cost. The variance is an indicator of the uncertainty involved in final costs. The greater the variance, the greater the uncertainty of the estimate.

Probability

There is a substantial disagreement among decision theorists and statisticians as to the essential meaning of probability. This controversy is centered around two distinct points of view, the objectivist and the subjectivist. The objectivist point of view relates probability to a frequency of occurrence (30:51). Probability, according to this viewpoint, is a statistic estimated from repeated observations of some directly observable phenomena (82:xii). According to the subjectivist viewpoint, the probability of an event is the degree of belief or degree of confidence placed in the occurrence of an event by a particular individual, based upon that individual's experience (3:17).

The objectivists believe that, on the basis of a given body of evidence, there is only a single value for the probability of the truth of a statement. The subjectivists hold that such a probability need not be unique and it is not uniquely defined. The probability may take on any numerical value between 0 and 1 corresponding to the level of belief of the estimator (30:51).

Probability from the objectivist point of view has proven highly successful in many applications which rest upon the existence of a stable, physical process of which repeated observations can be made (82:xii). However, many real world decision makers face the necessity of taking definite action in the face of substantial uncertainty regarding the outcomes of nonrepetitive phenomena. In such situations where no data or very little data exists, subjective probability provides the only alternative to quantifying the uncertainty in cost estimates (3:19; 82:xiii).

The process by which military cost estimates are generated does not constitute stable, repetitive phenomena to which the objectivist probability viewpoint is an applicable concept. Therefore, the assumption that subjective probability provides the best means of quantifying the uncertainty in cost estimates was advanced for the proposed research.

In an examination of the methodology of risk assessment within the U. S. Air Force Aeronautical Systems Division (ASD), Williams concluded that:

> . . . the method best suited for quantifying uncertainty would be subjective probability distributions . . . . This was, however, the most infrequently used and least widely known method of those surveyed [100:26].

In another paper devoted to the subject of risk analysis for the materiel acquisition process, Hwang

concluded that "techniques to collect subjective judgements must be developed further [52:62]."

The final report of the USAF Academy Risk Analysis Study Team, sponsored by ASD, concluded that in the area of quantitative risk assessment, aggregation output techniques (such as network analysis) are far more advanced than the techniques for obtaining input data (such as subjective probabilities). The study team recommended that "funding priority for improving methods for quantitative risk assessment should be given to the development of input techniques [60:8]."

This research effort should contribute to the development of subjective probability assessment techniques to assess the magnitude of uncertainties present during the weapon system acquisition process and to the integration of these techniques into the weapon system acquisition process.

SCOPE

The research will evaluate subjective probability assessment techniques, and will provide a technique for use in quantifying the magnitude of uncertainty in the weapon system acquisition process.

OBJECTIVE

The research objective is to evaluate existing subjective probability assessment techniques, in order to propose an approach which will best assess the magnitude

of uncertainty which exists relative to a given weapon system's development.

RESEARCH QUESTION

What existing subjective probability assessment technique would best assess the magnitude of uncertainty in a given weapon system's development effort?

Chapter 2

BACKGROUND

OVERVIEW

This chapter first presents classifications of weapon system program uncertainties from the standpoint of both the Department of Defense (DOD) and the contractor. The value of these classifications lies in the breaking down of the weapon system acquisition uncertainty problem into its component parts. Secondly, the chapter views the statistical and psychological aspects of subjective probability. Subjective probabilists attempt to characterize the collection of probability judgements that are admissible from a normative standpoint, while psychologists attempt to describe the actual mechanisms by which individuals assess probability. Next, the chapter describes six techniques for assessing subjective probabilities. Lastly, the chapter examines what subjective probability assessment procedures are required in weapon system source selection.

WEAPON SYSTEM UNCERTAINTIES

The U. S. Air Force (USAF) Academy Risk Analysis Study Team, sponsored by the USAF Aeronautical Systems

Division (ASD), classified weapon system uncertainties into four categories: target, internal program, process, and technical (60:23-30). Target uncertainty is the uncertainty involved in reducing a need to cost, schedule, and performance goals. Internal program uncertainty is the uncertainty inherent in selecting a particular method or strategy for dealing with a given problem. Process uncertainties concern military service priorities, other weapon programs, DOD policy, the budget submitted to Congress by the President, and congressional policy considerations. Technical uncertainty treats the question of whether a system can be developed at all, or the degree of difficulty which will be involved in building it. A list of uncertainties is attached as Appendix A for reference (52:63-65).

The above classification of uncertainty is from the point of view of DOD acquisition of weapon systems. Lenox gives another classification of the uncertainties involved in large government weapon system programs from the viewpoint of the contractor. These uncertainties are (58:18-19):

1. The size, nature, and timing of a future market for a weapon system.

2. Uncertainty of achieving technical design objectives within the constraints of time and resources available.

3. Uncertainty concerning whether designs are producible.

4. Risks due to phasing of functional tasks.

5. Tradeoffs between the cost of meeting the schedule and the penalties involved in not meeting the schedule.

6. The resources which are available or which can be made available in taking on or continuing a weapon system program.

7. The degree to which a contractor contractually obligates himself to both the government and other companies as subcontractors.

8. The value and accuracy of information which the contractor's decision makers can expect to receive.

Technical uncertainty can be further broken down into those items you know you don't know or the anticipated unknowns, and those items you don't know you don't know or the unanticipated unknowns (58:17). This may be one reason why the technical aspects of uncertainty have been overemphasized in the past, leading to inadequate considerations of other types of uncertainty in weapon acquisition programs. A study effort on quantitative risk assessment found that:

> Within DOD, there is little syntactical convention with regard to the term 'risk analysis.' On talking to members of other program offices within ASD, we found that 'risk analysis' generally infers analysis of what we have called 'technical uncertainty' [1:66].

The Air Force Academy Risk Analysis Team concluded that:

> . . . technical uncertainty was only the visible tip of the iceberg. Submerged beneath the surface and frequently having a far greater impact . . . were a number of additional uncertainties, none of them purely 'technical' in origin . . . [60:22-23].

SUBJECTIVE PROBABILITY

Statistical Aspects

Eisner and McDonald (30:52) traced the evolution of some of the underlying ideas and terms of subjective probability. Terms that were of interest were "degree of belief" and "coherence."

The term "degree of belief" was attributed to Bernouilli. In 1713, he used the expression "degree of confidence" in the sense that since the occurrence of an event cannot be predicted with certainty, there is only a "degree of confidence" in the assertion of the occurrence. In 1847, DeMorgan specified probability in terms of a measurable degree of belief that could be related to personal feeling. Ramsey and Borel in the 1920's noted that the individual's degree of belief has a direct correspondence to observable behavior in decision making. The minimum odds that a person will accept in a betting situation are a measure of that person's degree of belief. The property of coherence introduced by Ramsey insures that the person can never accept a bet or a set of bets which he can lose. Strict coherence as attributed to Shimony requires that the bettor accept odds such that he always wins a net amount (30:52).

Provided that such "degrees of belief" are assessed quantitatively and in a coherent manner, the probabilities so assessed can be shown to conform to the axioms of probability theory (26:110). If the events are mutually exclusive and collectively exhaustive, the axioms which the probabilities must meet are as follows:

1. The sum of the weights assigned to any set of mutually exclusive and collectively exhaustive events is equal to 1.

2. The weight assigned to any event shall be a number between 0 and 1, inclusive, 0 representing complete conviction that the event will not occur and 1 representing complete conviction that it will occur.

3. If two or more mutually exclusive events are grouped into a single event, the weight attached to this single event shall be equal to the sum of the weights attached to the original events.

In subjective probability assessments there is no correct or objective probability; the probability of an event is what the assessor believes it to be. From the assessor's viewpoint, no assessment can be wrong provided it is coherent; made with due care; and made with consideration of all known, relevant facts. Subjective probability theory does not prescribe what opinions people should have, but rather how their opinions should be held and modified on receipt of new information (49:271). At any given point of time the decision maker's (or expert's) state of

information about some uncertain quantity can be represented by a set of probabilities. When new information is obtained, these probabilities are revised in order that they may represent new information.

Psychological Aspects

De Finetti has stated that:

> The true . . . subjective probability . . . problem consists in the investigations concerning the ways in which such abilities may be improved. This seems to me the field in which the cooperation between all specialists concerned is most wanted, and that is particularly true for the expected contribution from psychologists [49:271].

Cognitive psychology is that branch of psychology which includes the study of perception, problem solving, judgemental processes, thinking, concept formation, and human information processing. This branch of psychology has directed its effort toward understanding the mechanisms by which man confronts and interprets stimuli with which he is faced and particularly toward specifying man's abilities and limitations as an information processing system (49: 272).

Much of this cognitive psychology research effort can be criticized on at least two accounts:

1. Research of human behavior in inferential, and decision making situations has included a considerable amount of experimental work, much of which has been simple, artificial situations. The artificial nature of these situations renders their generalization to realistic situations tenuous, thus leaving implications of the

results for actual real world situations questionable (105:252,260).

2. Most studies have involved people as subjects who are neither substantive nor normative experts. Substantive expertise refers to knowledge which the assessor has concerning the subject matter of interest; normative expertise is the ability of the assessor to express his opinions in probabilistic form (49:272).

The study of judgemental processes has produced two general conclusions:

1. Man has limited information processing capacity.

2. The nature of the judgemental task with which man is faced determines to a large extent the possible strategies he may use to deal with that task (49:272).

Given only limited processing capability, man is forced to function in a serial fashion in that he cannot simultaneously integrate a large amount of information. Furthermore, man must act in a selective manner in order to simplify his environment (50:299). The result, according to Hogarth, a psychologist, is that man is a "selective, stepwise information processing system with limited capacity, . . . he is ill equipped for assessing subjective probability distributions [49:273]."

Winkler, a subjective statistician, disagrees with Hogarth's claim that man is ill suited to assess probability distributions. Winkler uses as an example of good performance documented by a large body of data, weather forecasts

of precipitation. On the average, subjective precipitation forecasts have been as good as or better than probability forecasts determined by objective means (103:290).

Lichtenstein found that subjects who appear to do poorly in a complex probability estimation exercise may be making careful estimates based on a different data-generating model than the one used by experimenters. Lichtenstein performed a study to explore the ability of subjects to estimate probabilities. The study on the surface demonstrated that the subjects' responses differed from the correct (true) values, resulting in the conclusion that the subjects were poor probability estimators. However, careful examination revealed that many of the subjects were really careful and consistent probability estimators--they were simply using a different data-generating model than the experimenters (59:62).

Uncertainty is considered implicitly by obtaining the information concerning uncertainty and factoring it into the decision making process just as information about several other factors is integrated in the decision maker's or expert's mind. Uncertainty is considered explicitly by expressing it in probabilistic form (99:163-164).

The opinion an expert is asked to reveal is, implicitly or explicitly, his evaluation of certain probabilities. This is particularly brought out by Grayson, discussing geologists' evaluation of the success of a proposed oil-well drilling. Grayson states:

> Actually, operators are obtaining a form of personal probabilities from their geologists at the present time, although they do not refer to them by such a term. . . .
>
> Numbers . . . are merely another form of language, permitting subjective judgement to be put into a more precise form, a form which is tractable when relating the expert's evaluation to other facets of the drilling problem [39:255].

Hogarth also notes that man frequently ignores uncertainty--the reduction or omission of uncertainty itself being a useful cognitive simplication mechanism (49:273). Winkler responds by asking whether uncertainty is ignored or simply considered implicitly rather than explicitly (103:291).

Hogarth's rejoinder to Winkler is based upon the concept that ignoring uncertainty can be conceived on two levels. At one level, man in a complex situation may mentally replace a set of uncertainties with their certainty equivalent. At the other level, uncertainty causes anxiety which man attempts to avoid (51:294).

Even in the "rational" business world, there is evidence that businessmen avoid uncertainty. The studies of Cyert and March indicate that business organizations avoid uncertainty in two ways:

1. They solve pressing short-run problems rather than developing long-range strategies, thus avoiding the requirement that they correctly anticipate future wants.

2. They avoid planning, where plans depend upon prediction of uncertain events, by imposing standard

operating procedures, industry tradition, and uncertainty-absorbing contracts on the environment (18:119).

Given limited information processing ability, man structures his environment. When faced with the task of estimating statistics intuitively from data in experiments, subjects have been fairly accurate at guessing central tendency values, but not variances of the data (49:274).

In an experiment subjects saw samples of each of two populations of numbers and made intuitive inferences about which population had the larger variance. They then either estimated the ratios of the variances or stated their confidence (subjective probability) in their inferences. These ratios were used to infer the subjective magnitudes of the sample variances. The inferred ratios were inaccurate because of the subjects' tendency to underweight deviant sample data, and because the subjects regarded the variance of large numbers as less variable than the variance of small numbers (7:109).

Subjects also tend to assess distributions which are shaped like the normal distribution. While Winkler has suggested that this is due to the emphasis on the normal distribution in statistics courses, Hogarth believes that it is due to the human perceptual desire for symmetry (49:275).

Until recently, research concentrated on ascertaining how human judgements deviate from a normative statistical model. However, Kahneman and Tversky have focused

on the question "how do people evaluate uncertainty" rather than on "how well do people evaluate uncertainty" (53:452). The theme of Kahneman and Tversky's research is that judgements under uncertainty are based upon a limited number of mental operations, or heuristics. When faced with the difficult task of judging probabilities, people employ heuristics to reduce these judgements to simpler ones. Kahneman and Tversky have described four such heuristics: the law of small numbers, judgement by adjustment, judgement by representativeness, and judgement by availability.

The law of small numbers is the belief that even small samples are highly representative of the population from which they are drawn. People expect any two small samples drawn from a particular population to be more similar to one another and the population than sampling theory predicts (93:105). Kahneman and Tversky's study of experienced research psychologists demonstrated that the psychologists overestimated the statistical significance of a small sample, overestimated the replicability of the results, and rarely attributed a deviation of the results to sampling variability (93:109).

In judgement by adjustment, individuals estimate an unknown value by starting from some initial value which is then adjusted to yield the final answer. The initial value may be suggested by the problem or may be the result of a

partial computation. Different initial values yield different final estimates, which are biased toward the initial value (91:153-154).

An individual who follows the representativeness heuristic evaluates the probability of an uncertain event, or a sample, by the degree to which it is similar to its parent population, and the degree to which it reflects the features of the process which generated it (53:431). When the event or sample in question is highly representative of the process from which it originates, its probability is judged high. If the event is not representative, its probability is judged low (91:149).

The representativeness heuristic approach leads to serious biases because several of the factors that should be considered in evaluating probability have no role in judgements of similarity. One of these factors is prior probabilities; another is the size of the sample. To evaluate the probability of obtaining a particular result in a sample drawn from a specific population, people assess the degree to which the sample is representative of the population. The similarity of a sample statistic to a population parameter is unaffected by the size of the sample (91:150).

An individual is said to have used the availability heuristic whenever he estimates frequency of probability by the ease with which instances or associations can be brought to mind (92:208). Availability provides a mechanism

by which occurrences of extreme utility or disutility may appear more likely than they actually are.

Like representativeness, availability is useful for assessing frequency or probability. Both heuristics use mental effort to gauge subjective probability. However, availability is affected by factors such as familiarity, salience, or recency.

The major difference between the representativeness and availability heuristics is in the nature of the judgement which underlies the evaluation of subjective probability. According to the representativeness heuristic, one evaluates subjective probability by the degree of correspondence between the sample and the population. On the other hand, in the availability heuristic, subjective probability is evaluated by the difficulty of retrieval and reconstruction of instances. Thus, the representativeness heuristic is more likely to be employed when events are characterized by their general properties; while the availability heuristic is employed when events are characterized in terms of specific occurrences (53:452).

An important issue is whether the expression of judgement in probabilistic form is meaningful to both assessors and the recipients of such opinions. In Hogarth's view, there are three necessary conditions for probability assessment to be considered meaningful from the assessor's viewpoint:

1. The task should be meaningful to the assessor in that he is reasonably familiar with it.

2. Justification for the assessment depends on the extent to which it can predict more accurately than the best available statistical model.

3. Judgements expressed in probabilistic form are more accurate and useful than those expressed normally (49:278-279).

Another important issue in subjective probability assessment is the effects of different methods of eliciting subjective probability distributions. Winkler has stated:

> It must be stressed that the assessor has no built-in prior distribution which is there for the taking. That is, there is no 'true' prior distribution. Rather, the assessor has certain prior knowledge which is not easy to express quantitatively without careful thought. An elicitation technique used by the statisticians does not elicit a 'true' prior distribution, but in a sense helps to draw out an assessment of a prior distribution from the prior knowledge. Different techniques may produce different distributions because the method of questioning may have some effect on the way the problem is viewed [104:778].

As far as the relative merits of the different techniques are concerned, the results of isolated experiments in the assessment of continuous probability distributions have been contradictory. However, for estimation of discrete probability distributions, an experiment has shown reasonable consistency between probability estimates inferred from bets and direct assessments (6).

Consistency between different assessment methods appears to be governed by the depth of the assessor's

knowledge of the elicitation method used. Naive subjects show inconsistencies between different methods in assessing continuous variables, while they show fairly consistent responses in assessing fairly simple discrete events. Normative experts show little inconsistency between different methods (49:279), demonstrating that statistical training is of great help in assessing probabilities (49:282).

According to Hogarth, a body of systematic psychological experimental information in this area of subjective probability is lacking. A major question is how to deal with the experimental data to date in which naive subjects have yielded responses utilizing subjective probability techniques which they did not fully understand. Furthermore, the effects of differences in personality and background have rarely been examined in the experiments (49:284). Winkler feels that cognitive psychology "may have important implications for probability assessment, and further work needs to be done to investigate such implications [103:290]."

SUBJECTIVE PROBABILITY ASSESSMENT TECHNIQUES

Techniques for assessing subjective probabilities are relatively recent; their application to statistical problems has occurred mainly in the post World War II era (3:17). The assessment techniques below have been developed

for eliciting an expert's assessment of the probability of an occurrence of an event.

<u>The Choice-Between-Gambles Technique</u>

This technique employs betting-type or gambling situations to elicit probability density or cumulative probability density functions (3:23). To obtain a probability density function, the expert is offered a choice between a real-world gamble involving values of the item under consideration with unspecified probabilities, and a hypothetical gamble involving two events with given probabilities (3:25). Consider an example from Atzinger involving a design thrust for a jet engine (3:25-27). Initially, the expert is offered these choices:

1. Real-world gambles--a payoff of $10 if the thrust reached is 36,000 ± 1,000 lb. with unknown probability, and a payoff of $0 if the thrust reached is not 36,000 ± 1,000 lb. with unknown probability.

2. Hypothetical gamble-- a payoff of $10 if event E_1 occurs, with the probability of E_1 occurring being 0.5 ($P(E_1) = 0.5$); or $0 if event E_2 occurs with probability 0.5 ($P(E_2) = 0.5$).

If the expert's decision in the first round is to accept the real-world gamble, it is inferred that his subjective probability assessment that a thrust of 36,000 ± 1,000 lb. will be achieved is greater than 0.5. Thus, in the next iteration, the analyst adjusts the probability of

occurrence of hypothetical event E_1 upward and event E_2 downward; this procedure is continued until the expert is indifferent to choosing between the two gambling situations. If this stage is reached at $P(E_1) = 0.7$, $P(E_2) = 0.3$, then it is inferred that P(thrust = 36,000 ± 1,000 lb.) = 0.7. The thrust value is then changed by an interval chosen so that the expert can discriminate between its probability of occurrence and the previous value; for example, from 36,000 lb. to 34,000 lb. This procedure is continued until a probability distribution is obtained, as shown below:

Thrust	Probability
32,000 ± 1,000	0.0
34,000 ± 1,000	0.2
36,000 ± 1,000	0.7
38,000 ± 1,000	0.2
40,000 ± 1,000	0.0

If the sum of the probabilities is greater than one, as above, the analyst reassesses the expert's probabilities or normalizes the derived probabilities by dividing each one by the sum of all the subjective probabilities (3:27).

In obtaining a cumulative distribution function the probabilities of occurrence of E_1 and E_2 are fixed, while the characteristic values of thrust are changed until indifference is achieved (3:29). Thus, the probabilities of E_1 and E_2 would be fixed at 0.5; the initial indifference point would give the value of thrust for which the

probability was 0.5. The next iteration would obtain a value for thrust which equally divided each of these intervals; that is, the thrust values for which the probabilities were 0.25 and 0.75. This procedure is iterated until an upper thrust value is reached with a probability equal to 1, as shown below:

Initial Iteration

$$\begin{tikzcd} & P(T_1) = 0.5 \arrow[dl] \arrow[dr] & \\ P(T_2) = 0.250 \arrow[d] & & P(T_3) = 0.750 \arrow[d] \\ P(T_4) = 0.125 \arrow[d] & & P(T_5) = 0.875 \arrow[d] \\ P(T_L) = 0.000 & & P(T_U) = 1.000 \end{tikzcd}$$

The lowest thrust value is T_L, and T_U is the upper thrust value. The values can then be combined in ascending order to obtain the cumulative distribution.

The Standard Lottery Technique

The objective of this technique is the derivation of a probability density function over all possible values of a given component characteristic. Like the Choice-Between-Gambles technique, this technique presents the expert with two gambling situations. However, the technique differs from the Choice-Between-Gambles technique in that it does not involve the process of varying probabilities or performance levels until indifference is achieved.

Instead, the number of lottery tickets from a pool of 100 is varied in an attempt to achieve expert indifference.

The technique is based upon the following standard lottery procedure. In a lottery with 100 tickets, a contestant can purchase as many tickets as he desires; the greater the number purchased the greater the chance of his winning. After the purchase of tickets is completed, one random number between 1 and 100 is drawn. The winning contestant is that individual who purchased the lottery ticket with that number.

In this technique the expert is presented with a hypothetical lottery of 100 tickets. The lottery is used as a standard of comparison in helping the expert decide what probability value to assign to the possible realization of a given characteristic level of an event. The questioning procedure is as follows:

1. Specify a possible value (e.g., thrust = 36,000 lbs.) for the relevant real world event (e.g., experimental jet engine thrust).

2. Have the expert imagine that he is given a choice between a certain number of tickets in a standard lottery with a prize value V and the right to receive the same prize if the value of the real world event is realized (e.g., jet engine thrust = 36,000 lbs.).

3. For a given initial number of lottery tickets, ask the expert which alternative gamble he feels has the greatest chance of winning the prize: a) the holding of

the specified number of tickets of a lottery with 100 tickets outstanding, or b) the realization of the value of the real-world event.

4. If one of the alternative gambles is preferred over the other, next vary the number of tickets (e.g., increase the number if the expert chooses the real-world event in step 3, decrease the number if he chooses the lottery alternative) and repeat step 3.

5. Repeat steps 3 and 4 until the expert feels that the possibility of receiving the prize for the value of the event (engine thrust = 36,000 lbs.) has exactly the same likelihood as say, 70 tickets in the standard lottery. Thus it can be inferred that the expert considers both alternatives equally likely, and a probability of 0.7 can be assigned to the event thrust value = 36,000 lbs.

6. Using steps 1 through 5, the expert can proceed to similarly assign probabilities to all other possible values of the real world event (3:34-36).

The Modified Churchman-Ackoff Technique

This technique differs from the preceeding techniques in that it does not involve betting situations, and the expert is not asked to reveal indifference values of the parameter in question. The expert is instead asked to make "greater than," "equal to," or "less than" evaluations regarding relative probabilities between two sets of values and relative probability assessments with respect to the

most probable characteristic value. The resultant relative probability scale is easily transformed into a probability density function.

With this technique, the expert must decide upon a range of possible values which the relevant event could realize. He must specify the values for the range end points which have zero probability of occurrence.

Next, individual values within the range of possible values must be determined. These values are determined through the following approach:

1. Start with the smallest end point value.

2. Progress upward from the smallest end point value until the expert is able to state a simple preference regarding the relative probabilities of occurrence of the two values. If the expert believes that one or the other has a greater chance of occurrence than the other of the two values, it can be inferred that the expert is able to discriminate between the two values.

3. Using the higher of the two previously identified values, repeat step 2 to determine the next value within the range.

4. Repeat steps 2 and 3 until the high end point of the range of values is approached.

For example, using this procedure for the thrust of a jet engine in development, the results in Table 1 are obtained.

TABLE 1

Range of Values for Thrust Example

$T_1 = 35{,}000$
$T_2 = 36{,}000$
$T_3 = 37{,}500$
$T_4 = 38{,}500$
$T_5 = 40{,}000$
$T_6 = 41{,}000$
$T_7 = 41{,}500$

The descending order of probability of occurrence for each value can be determined by applying the following paired comparison method.

Ask the expert to compare the first value T_1 to each of the other values, and state a preference for the value in each pair that he believes has the greater chance of occurring (denoting a greater probability by >, an equal chance by =, and a lesser chance by <). The following hypothetical preference relationships could result from the set of seven values in Table 1: $T_1 < T_2$, $T_1 < T_3$, $T_1 < T_4$, $T_1 < T_5$, $T_1 < T_6$, $T_1 = T_7$.

Next, ask the expert to compare the second value T_2 to each of the other values succeeding it in the set. Continue the process until all values have been compared to the others in like manner. Table 2 lists the preference relationships which might result.

TABLE 2

Paired Comparisons

T_1	T_2	T_3	T_4	T_5	T_6
$T_1 < T_2$	$T_2 < T_3$	$T_3 < T_4$	$T_4 > T_5$	$T_5 > T_6$	$T_6 > T_7$
$T_1 < T_3$	$T_2 < T_4$	$T_3 > T_5$	$T_4 > T_6$	$T_5 > T_7$	
$T_1 < T_4$	$T_2 < T_5$	$T_3 > T_6$	$T_4 > T_7$		
$T_1 < T_5$	$T_2 > T_6$	$T_3 > T_7$			
$T_1 < T_6$	$T_2 > T_7$				
$T_1 = T_7$					

Now total the number of times each T_i value was preferred over the other values. The results of this procedure are listed in Table 3. List the thrust values in descending order of preference, and change the symbols for each value from T_i to X_j, as shown in Table 4.

TABLE 3

Summary of Preference Relationships

T_4 = 6 times
T_3 = 5 times
T_5 = 4 times
T_2 = 3 times
T_6 = 2 times
T_1 = 0 times
T_7 = 0 times

TABLE 4

Transformations

Characteristic Value	Preference Rank	New Symbol
38,500 (T_4)	1	X_1
37,500 (T_3)	2	X_2
40,000 (T_5)	3	X_3
36,000 (T_2)	4	X_4
41,000 (T_6)	5	X_5
35,000 (T_1)	6	X_6
41,500 (T_7)	7	X_7

Arbitrarily assign a rating of 100 points to the thrust value with the highest subjective probability, or preference rating (e.g., X_1). Then, as in the first step, question the expert regarding the relative chance of occurrence of each of the other values on the ordinal scale in Table 4 with respect to the values above them on the scale. Assigning X_1 a rating of 100 points, the expert is interrogated as to his feeling of the relative chance of occurrence of the second highest scale value, X_2, with respect to X_1. For example, if the expert decides that X_2 has .8 as much chance of occurring as X_1, the ratings become X_1 = 100 points and X_2 = 80 points.

The expert is then questioned about the relative chance of occurrence of the next highest scale value X_3, first with respect to X_1, then with respect to X_2. The resulting numerical ratings should concur. If the expert expresses a belief that X_3 has .5 as much chance as X_1 of occurring, and 5/8 as much chance as X_2 (as a validity check), this confirms that the relative probability of occurrence rating for X_3 is 50 points.

Continue the process for each remaining value on the ordinal scale in Table 4. Determine the relative number of points to be awarded each value with respect to the top scale value, and with respect to all other values on down the scale which are above the value in question.

In the event of disparities between relative probability ratings for a certain value, the expert should

be asked to reevaluate his relative ratings. If this is not successful, the average of all such ratings for a given X_i value should be computed, and used as a relative probability rating.

As a result of the above process, the relative probability ratings shown in Table 5 might be attained.

TABLE 5

Relative Probability Ratings

RX_1 =	100 points
RX_2 =	80 points
RX_3 =	50 points
RX_4 =	25 points
RX_5 =	10 points
RX_6 =	0 points
RX_7 =	0 points

Finally, the scale of relative probability values can be converted to probability density values, using the following relationships (where $P(X_i)$'s are probabilities and the RX_i's are relative probability ratings):

$$P(X_i) = \frac{RX_i}{RX_1} P(X_1) \quad \text{for } i = 2,3,4,5,6,7$$

$$\Sigma P(X_i) = 1 \quad \text{for } i = 1,2,3,4,5,6,7$$

These two relationships will give a system of linear equations from which the values of each $P(X_i)$ can be computed. The results of the example are shown in Table 6 (3:36-43).

TABLE 6

Probability Density Function

Symbol	Thrust Value	Probability
X_1	38,500	0.377
X_2	37,500	0.301
X_3	40,000	0.189
X_4	36,000	0.095
X_5	41,000	0.038
X_6	35,000	0.000
X_7	41,500	0.000
		1.000

<u>The Delphi Technique</u>

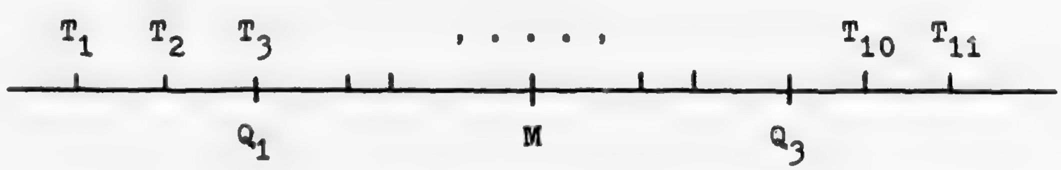
The Delphi technique is an alternative to the committee approach for eliciting group judgement. It attempts to improve this judgement by removing barriers to effective group judgement, such as dominant individuals, communication "noise," and group pressure toward conformity (21:v).

A group probability assessment may be obtained with this technique. Anonymous individual probability responses are elicited from each group member using questionnaires (or a similar device). The group response is collected by analysts, who summarize the responses and feed them back to the group. Individuals may be asked to justify assessments which are extreme in comparison to the group. The group members are requested to make any probability assessment changes they desire based upon the feedback presented to them. This procedure is iterated until group members make no further changes in their assessments. The analysts then summarize and define the final group response, usually by averaging final responses, or selecting the median response (3:24).

An example follows to clarify the Delphi Technique (72:334-335):

First, suppose we wish to arrive at how large the thrust, T, for an experimental jet engine will be. The following steps are involved:

1. Ask each expert independently to give an estimate of T, arrange responses in order, and group them in quartiles Q_1, M, Q_3 as shown:



2. Communicate Q_1, M, and Q_3 to each expert, ask him to reconsider his previous estimate, and if his estimate (old or revised) lies outside the interquartile range (Q_1 to Q_3), to state his reason.

3. Communicate the results of this second round, plus the reasons, to the respondents in summary form, and ask for new estimates and arguments.

4. Repeat steps 2 and 3 until no further changes are made by the respondents, or the dispersion among responses is acceptable. Take the median to represent the group decision as to the value of T. The "smallness" in dispersion depends on the criticality of T for the desired purpose.

The DeGroot Consensus Method

DeGroot has proposed a model for reaching group consensus. Each group member, or expert, must first assess a probability distribution for the unknown value of some parameter. He is then confronted with the probability distributions of the other group members, and revises his own opinion in light of the others by making an assessment of each group member's relative importance, expertise, etc. Given that each group member revises his opinion in this manner, to be consistent each member should update his own probability in response to revisions made by the other group members. The process continues until further revision no longer occurs. DeGroot showed that this process can be

interpreted within the theory of Markov chains, the limit theorems of which can be used to see whether a consensus distribution exists, and if so, what it is (27:118-21).

The Direct Estimation Technique

This technique results directly in a probability density function as the individual expert approximates the probabilities without benefit of one of the techniques for inferring probabilities that were described earlier.

APPLICATION OF SUBJECTIVE PROBABILITY ASSESSMENT TO WEAPON SYSTEM SOURCE SELECTION

Little information has been found concerning the extent to which subjective probability assessment techniques have been utilized in the weapon system acquisition process due to the confidentiality involving source-selection documents. DOD Directive 4105.62, "Selection of Contractual Sources for Major Defense Systems," establishes DOD objectives, principles and policy for the evaluation of proposals in the selection of contractual sources for each system/project. In accordance with the Directive, Government solicitations for contractor proposals must require the competitors to identify technical risks and uncertainties and suggest realistic approaches to their resolution (95:11). The Directive does not go into detail on any recommended subjective probability assessment procedure for assessing uncertainty in a source-selection cost estimate.

Air Force Regulation (AFR) 70-15, "Source Selection Policy," 22 June 1973, implements DOD Directive 4105.62 within the Air Force, and is the basic Air Force Directive pertaining to source-selection actions (97). Air Force Manual 70.6, "Source Selection Procedures," 22 June 1973, defines the guidelines contained in AFR 70-15 and prescribes general procedures to be employed in major source selection actions (96). Both the Regulation and the Manual call for the source-selection process to focus attention on technical risk and uncertainties for major developmental programs. The Air Force solicitation to potential contractors should identify potential areas of high risk if there is a reason to believe that the risks are not generally known to the offerors. The offerors should identify technical risks associated with their proposals and the possible impacts on cost, schedule, or performance, together with realistic approaches to their resolution. Risk analysis is identified as part of the source-evaluation process, and risk assessments for each proposal must be included in all reports to the Source Selection Advisory Council. Technical risk should be an evaluation criteria element, and should be rated based upon the offeror's risk assessment and the credibility of the offeror's proposed approach for elimination or avoidance of the risk (96:3-5 to 3-6; 97:4-5). Neither the Regulation nor the Manual go into any detail on any recommended subjective probability assessment procedure.

Air Force Systems Command Regulation 70-9, "Source Selection Procedures," 16 August 1974, addresses itself to procedures for source-selection actions below the dollar thresholds established by AFR 70-15 (94). This Regulation leaves to the discretion of the Source Selection Authority whether the evaluation and rating system of the offeror's proposals should be:

1. Substantially and predominantly mathematical scoring;

2. Partial scoring and partial subjective assessment; or

3. Wholly subjective analysis and assessments.

The Regulation relates that there has been a swing from numerical scoring to rating proposal elements using color-coded narrative assessments for briefings. The following, as described by the Regulation, is a subjective assessment color-coding system frequently used:

> 1. Green--exceeds specified performance or capability and excess is useful; high probability of success; no significant weakness;
> 2. Blue--average; meets most objectives; good probability of success; deficiencies can be corrected;
> 3. Yellow--weak; low probability of success; significant deficiencies; but correctable;
> 4. Red--key element fails to meet intent of the Request for Proposal (RFP) [94:45].

The ASD Handbook on the source-selection process (98) states that a risk analysis will be performed during source selection, but it also fails to go into detail on any recommended subjective probability assessment

procedures for assessing the uncertainty in a source-selection cost estimate.

Chapter 3

RESEARCH METHODOLOGY

OVERVIEW

The research team evaluated the subjective probability assessment techniques using content analysis. The population considered in the study consisted of the subjective probability techniques defined in Chapter 2. The population and sampling plan, content analysis, coding plan and categories, pilot study, reliability of the code, coding and summarization of the units of content, summary of assumptions, and summary of limitations are described below.

POPULATION DESCRIPTION AND SAMPLING PLAN

The population of subjective probability techniques was sampled by reviewing pertinent subjective probability literature as identified in Table 7. The sample time period of convenience covered was from January, 1960, to the present. The sampling plan was a nonrepresentative sample of convenience. The researchers attempted to reduce the bias resulting from the sampling plan by sampling, within the time constraints placed on the research team, as broad a range of literature as possible in terms of time,

application, and theory. A listing of the sources used in the content analysis, by technique, can be found in Appendix B.

TABLE 7

Sampling Sources

Source	Index Identifiers
Books--in Libraries of: AFIT Engineering School; AFIT School of Systems and Logistics; Wright State University	Decision Theory (Library of Congress Codes HD 38, HD 69) Probability Theory (QA 273-279) Psychological Theory (BF 38-39, BF 441)
Business Periodicals Index	Probabilities
Defense Documentation Center/Defense Logistics Studies Information Center	Cost Uncertainty Analysis Decision Making Decision Theory Delphi Prediction Methods/Forecasting Probability Theory Risk Analysis
Mathematical Reviews	Probability
Psychological Abstracts	Cognitive Processes and Motivation Decision and Choice Behavior Decision and Information Theory Learning and Memory Learning, Thinking, and Conditioning
Statistical Theory and Methods Abstracts	Probability

CONTENT ANALYSIS

The methodology which was selected to answer the research question and meet the research objective was content analysis. Content analysis has been variously described as a "research technique for the objective, systematic, and quantitative description of the manifest content of communication [8:18]," and as "a procedure of classification, summarization, and tabulation [34:646]."

The most basic distinction made in content analysis is between content analysis done at the manifest level, and content analysis done at the latent level. Content analysis at the manifest level is analysis of what the material being analyzed literally stated. In contrast, content analysis at the latent level goes beyond what the material being analyzed said literally in order to make inferences about what the material implied or meant. Evidence has indicated that content analysis at the manifest level is reliable and valid; this was not true of content analysis at the latent level (34:647-48). The research effort used content analysis at the manifest level.

There were three basic steps in applying the content analysis technique: 1) deciding what the unit of content, or material to be categorized, would be; 2) developing the set of categories; and 3) developing a coding rationale to guide the placement of the unit of content into categories (34:649).

The first step was to select what is called the unit of content, or material to be categorized. Generally, this involved making a choice between using each sample in total, or breaking each sample down into the separate words or phrases which make it up (34:649,651). If it were decided to use each sample in total as the unit of content, each sample would be read completely and categorized on the basis of everything it contained. If the separate words or phrases in each sample were used as the unit of content, each separate word or phrase that indicated some specific perception of what was being analyzed would be categorized separately. The research used the phrase, here described as a word or group of words that form a unit expressing a perception, as the unit of content. Each phrase from the sample of previously identitied subjective probability techniques that indicated a specific perception dealing with one of the criteria categories specified below was coded.

To do the content analysis a set of categories and a method of coding was needed. In addition to reliability and validity, the desirable attributes of a set of categories were homogeneity, inclusiveness, usefulness, and mutual exclusiveness. Homogeneity is the property that each level of categories is similar in content and level of abstraction. Inclusiveness is the requirement that every unit of content be classified. Usefulness is defined as reflecting the fact that each category delineates a

meaningful dimension of the variable under study. Mutual exclusiveness is the attribute that there be one place and only one place to code any one unit of content (34:675-77). Minimally, the code should have face validity (34:672).

There were three aspects to each unit of content to be categorized by coding: the subjective probability technique, the criteria category, and the negative-positive valence. Valence expressed feeling tone, or how strong an element of personal statement was contained in the unit of content (34:659). Since there were three different aspects to code, the code consisted of three digits; the first digit dealt with the specific probability technique, the second digit with the criteria category, and the third digit with the negative-positive valence. The coding plan and categories established for this research are shown in Table 8.

Coding Plan and Categories

The first digit in the coding assigned the unit of content to one of the subjective probability techniques being evaluated. For example, if the unit of content being coded contained a perception dealing with the Choice-Between-Gambles technique, its coding began with the digit "1." This first level of categorization had all the previously defined desirable attributes of a set of categories, in that the subjective probability techniques being evaluated, with their corresponding first-digit code, were as

TABLE 8

Code for Content Analysis of Subjective Probability Techniques

First Digit: Subjective Probability Technique

1--Choice-Between-Gambles

2--Standard Lottery

3--Modified Churchman-Ackoff

4--Delphi

5--DeGroot Consensus Method

6--Direct Estimation

Second Digit: Criteria Category

1--Ease of Application

2--Adaptability and Flexibility

3--Validity and Reliability

4--Time

5--Removal of Bias

6--Miscellaneous

Third Digit: Valence Category

1--Negative

2--Mixed

3--Positive

follows: (1) Choice-Between-Gambles, (2) Standard Lottery, (3) Modified Churchman-Ackoff, (4) Delphi, (5) DeGroot Consensus Method, and (6) Direct Estimation.

The second digit in the coding was used to identify the criteria category. The categories served as a means of summarizing the relative attributes of the subjective probability techniques. For example, if the unit of content being coded contained a perception pertaining to the ease of application of the Choice-Between-Gambles technique, its coding started with the digits "11." The criteria categories also contained the previously defined desirable attributes of a set of categories: homogeneity, in that they were related to one another as criteria to evaluate the subjective probability technique; and usefulness, reflecting the fact that each criteria category served a purpose and delineated a criterion of the subjective probability techniques under study.

In order to make the criteria categories inclusive, a miscellaneous category was added as a way of including those units of content which did not fit a predetermined criteria category. After initial coding, the miscellaneous criteria category was surveyed for similar units of content. If these similar units of content constituted five percent of the total units coded, a new criteria category was added, and the similar units of content were placed in that new criteria category.

Each subjective probability technique was assessed with respect to the following criteria categories (see Appendix C for adjectives and phrases used to code the units of content to each criteria category):

1. Ease of application--this criteria category included: the level of expertise required of the analysts in preparing and administering the technique and in analyzing the results obtained from the technique; the requirements for defining and selecting respondents (experts); the training needed for analysts or respondents to use the technique; the money cost of the technique; and any unique equipment or facilities needed to apply the technique.

2. Adaptability and flexibility--this criteria category addressed the utility of the technique to the user in terms of: its application to more than one use; the limitations of the technique; the changeability of the procedures of the technique; the potential usefulness of the technique; and the ability of the technique to handle changes in the problem under consideration.

3. Reliability and validity--reliability here means that similar groups/individuals would make the same assessment using the technique. Validity pertains to the accuracy of the technique, or how close the results obtained from the technique are to what occurs in the real world. This area included: the replicability of the technique; the validity of the methodology and data obtained; the

precision and objectivity of the technique; the relative effectiveness of the technique compared to other techniques; the validity of the technique in dealing with real problems; and evidence demonstrating the reliability and validity of the technique.

4. Time--this criteria category addressed the time factor involved in using the technique, and included the length of time required to apply the technique; the time required to process the results; and the time needed to get the information obtained from the technique to the appropriate decision makers.

5. Removal of bias--bias in this category referred to the bias introduced in the results because of individual/group interactions among respondents; analyst or administrator bias; user bias; procedural bias; and bias due to information or the lack of information obtained using the technique.

6. Miscellaneous--this criteria category included any units of content not clearly belonging in the other criteria categories.

The third digit in the coding recorded the negative-positive valence with which a unit of content related a criteria category to a subjective probability technique. If the unit of content, for example, contained a negative perception dealing with the ease of application of the Choice-Between-Gambles technique, the coding was "111." The valence categories also satisfied the desired

attributes of a set of categories. To standardize the application of the valence categories, they (along with their coding) were defined as follows:

(1) Negative--a unit of content containing only perceptions of unacceptance or disapproval.

(3) Mixed--a unit of content containing both negative and positive elements.

(5) Positive--a unit of content containing only perceptions of acceptance or approval.

A list of adjectives and phrases which express negative, mixed, or positive valences can be found in Appendix D.

Pilot Study

Since satisfactory reliability cannot always be achieved, a pilot study is critical in any research in which content analysis will be used (34:648). The researchers each performed a pilot study of Elsbernd's unpublished research study, "The Use of the DELPHI Method Within the Defense Department" (31). This pilot study was performed in order to provide an estimate of the success the researchers would have if they used their version of content analysis to answer the research question, and in order to validate the reliability of the code. The results of the pilot study are discussed below under "Reliability of the Code."

Reliability of the Coders

In order to estimate the reliability of any single coder, it is necessary to have developed a standard set of approximately 100 coded units of content to which a number of individuals have agreed. The coder whose reliability is to be estimated then codes this standard set of units of content (34:670). Due to the lack of a standardized coding test for this thesis subject, it was assumed for the purpose of this research that both researchers were reliable coders.

Reliability of the Code

Reliability of the content analysis code was estimated by computing the percent of time that the two researchers agreed when they each coded the same sample of 27 units of content during the pilot study. The percent of agreement was computed as follows:

$$\text{Percent agreement} = \frac{\text{Number of units coded identically}}{\text{Total number of units coded}}$$

With the three-digit code being used in this research, 85 percent agreement was a realistic expectation (34: 669-670). After initially coding the same material, the researchers' percent agreement was 67 percent. Accordingly, the research team met to explain their rationale for their own coding of the data. Once the nature of the discrepancy was determined, the categories were reworded to eliminate the possibility of alternative interpretations. After a

second coding of the same material by each researcher, the percent agreement was 93 percent. The code thus met the 85 percent agreement criterion. The initial and recoded content analysis results are shown in Table 9.

TABLE 9

Summary of Pilot Study

		Initial Codes			Final Codes		
Unit of Content	Page	Coder 1		Coder 2	Coder 1		Coder 2
1	25	455		455	455		455
2	27	455	*	453	455	*	453
3	37	413	*	411	411		411
4	38	411		411	411		411
5	38	441		441	441		441
6	39	411	*	461	411		411
7	40	461		461	461		461
8	40	415	*	463	415		415
9	41	465		465	465		465
10	41	465		465	465		465
11	41	411		411	411		411
12	41	441		441	441		441
13	41	441		441	441		441
14	41-42	441		441	441		441
15	42	441		441	441		441
16	42	411	*	461	411		411
17	42	411	*	461	411		411
18	42	411	*	461	411		411
19	42	461		461	461		461
20	42	411	*	461	411	*	461
21	43	461		461	461		461
22	42	431	*	461	461		461
23	62	441		441	441		441
24	26	411		411	411		411
25	41	415		415	415		415
26	41	415		415	415		415
27	42	461		461	461		461

* Indicates disagreement

Initial percent agreement = 18/27 = 67 percent

Final percent agreement = 25/27 = 93 percent

Coding and Summarization of the Units of Content

In the actual process of the content analysis, units of content from the sample were coded by the research team. Once the units of content were fully coded, they were summarized by the researchers. The two levels of summarization which were obtained using the content analysis are displayed in Figure 1.

The first level of summarization obtained by the researchers was the relative frequency of occurrence of each three-digit code with the same first two digits. The frequency of codes 111, 113, and 115 was computed relative to each other, etc. Based upon the three-digit code with the highest relative frequency, each two-digit code was assigned a one, three, or five valence. In cases of ties the average of the tying valences was assigned. If code 111 had the highest frequency relative to 113 and 115, for example, then a one (negative valence) was assigned to the criteria category 11 (ease of application criteria relating to the Choice-Between-Gambles technique). Each other criteria relating to the Choice-Between-Gambles technique was assigned a one, three, or five valence. Each number thus assigned to a two-digit code was summed to its applicable first digit code (subjective probability technique); this was the second level of summarization. The sum of the valences assigned to the two-digit codes was the criteria evaluation of the subjective probability technique. The subjective probability technique with the

FIGURE 1

The Summarization Process of the Content Analysis

Technique		Criteria		Valence
	← Second Level of Summarization		← First Level of Summarization	
1 Choice-Between-Gambles		11 Ease of Application		111 Negative
		12 Adaptability and Flexibility		113 Mixed
		13 Validity and Reliability		115 Positive
		14 Time		
		15 Removal of Bias		
		16 Miscellaneous		
2 Standard Lottery				
3 Modified Churchman-Ackoff			[Summarization Repeated for Each Technique]	
4 Delphi				
5 DeGroot Consensus Method				
6 Direct Estimation				

largest sum value was selected as that technique which best answered the research question and met the research objective.

SUMMARY OF ASSUMPTIONS

1. Assessment of uncertainty regarding cost estimates is subjective.

2. Subjective estimates of uncertainty can be expressed in terms of probabilities.

3. The criteria for evaluating the subjective probability techniques were mutually exclusive, collectively exhaustive, and equally weighted.

4. The number of sources reviewed was sufficient to evaluate the subjective probability techniques.

5. The research team's version of content analysis is valid and reliable.

6. The researchers are reliable content analysis coders.

7. The Martin Cost Model is valid for future cost estimation.

SUMMARY OF LIMITATIONS

Conclusions of this study are limited to selecting the subjective probability technique which best assesses the magnitude of uncertainty in a weapon system acquisition.

Chapter 4

FINDINGS AND CONCLUSIONS

OVERVIEW

This chapter discusses the results of the content analysis by assessment technique, and sets forth the conclusions that the research team was able to draw from the content analysis.

RESULTS OF CONTENT ANALYSIS

The Choice-Between-Gambles Technique

The evaluation of this technique resulted in a score of 16, based on 57 units of content from nine sources (see Appendix B for the source listing for each technique). A narrative summary of each criteria category follows.

Ease of application. This criteria category received a one (negative) valence, based on a 76.4 percent relative frequency of occurrence of that valence. Representative comments by valence were:

1. Negative (76.4%)--The Choice-Between-Gambles technique is difficult to administer (55:41). The technique runs into difficulty when an individual is unwilling to risk any part of his capital, is unwilling to gamble with his own

money regardless of odds, or is unwilling to gamble on moral grounds (36:103,127). The expert must understand the concepts of probability. He may find difficulty in the determination of the highest or lowest value for which he can state a subjective probability, due to his limited ability to discriminate between values (3:64). The technique also requires extensive expert training, the application of a tedious methodology, and highly skilled and experienced analysts. Still another difficulty is that decision makers may rebel at the idea of playing a "game" to assess their subjective probabilities, and may not seriously participate or concentrate on their assessment task (55:41,47,66).

2. Mixed (11.8%)-- The technique assumes that the expert has normative and substantive expertise (3:34).

3. Positive (11.8%)--The technique is simple to apply and results directly in a probability density function (3:27).

Adaptability and flexibility. This criteria category received a three (mixed) valence, since two of the four units of content were mixed. Valence comments were:

1. Negative (25%)--The method suffers from being insufficiently general (73:73).

2. Mixed (50%)--The method produces only discrete probability functions (3:27). Providing that the stakes are not too large and assuming that utility problems do not arise, the betting situation can be used for assessment of subjective probabilities (102:23).

3. Positive (25%)--A rough check of someone else's probability against the standard betting odds is useful (11:336).

<u>Reliability and validity</u>. This category received a five (positive) score, based on a 39.2 percent relative frequency of occurrence. Representative comments were:

1. Negative (30.4%)--A primary limitation of the technique is the expert's ability to respond when through further subdivision the probability of occurrence of the interval becomes small (3:33). Another limitation is that the method is necessarily inexact; partly because of the diminishing marginal utility of money, and partly because a person may have special eagerness or reluctance to bet. The proposal of a bet may alter an individual's state of opinion (73:73), or may fail because the human mind has proven itself inept at estimating odds (36:103). Also, if the amount of money being bet is very small, the individual may be careless in judging the odds (36:103).

2. Mixed (30.4%)--The merits of the method are related to the expert's ability to respond easily and intelligently, and to the confidence that can be placed in the expert's response (87:45). The technique assumes that the monetary rewards are large enough to motivate the expert; that the expert has normative and substantive expertise; and that the expert is able to make more rational, consistent, and correct judgements when presented with gambles than if he were asked to directly estimate probabilities (3:28,34).

3. Positive (39.2%)--The Choice-Between-Gambles technique is fundamentally sound (73:73). The fact that the technique is generally axiomatically valid has been its main advantage. Many authors feel that this form of questioning approach results in a more realistic subjective density function than a direct questioning approach (3:24). The technique may prove useful in vague situations, since the consideration of betting situations helps to alleviate vagueness (102:97). Compared to other techniques, the technique results in a more valid density function (3:27); has a higher response confidence due to the ease of response (87:45); and is more realistic since it incorporates risk in its analysis (55:41).

<u>Time</u>. In this criteria category, since two units of content were negative and two were positive, the valences were averaged to give a score of three (mixed).

<u>Removal of bias</u>. A score of one (negative) was given to this criteria category, since all of the units of content were negative. Valence comments included:

1. Negative--The main problem with the technique is that different individuals may interpret or react differently to the same probability; thus, bias is introduced into the method according to how the decision maker perceives the probability (55:46). The "probabilities" of the gamble can be presented in several ways, and the way used will affect the behavior to be expected from the

appraiser (74:85). The individual's attitudes toward risk may also influence his decision (55:44,47; 74:23,85).

Miscellaneous. A score of three (mixed) was recorded in this criteria category. There was one unit of content in each valence, thus the valences were averaged to obtain the score of three.

The Standard Lottery Technique

The evaluation of the Standard Lottery technique resulted in a score of 24, based upon 33 units of content from nine sources. A narrative summarization of the content analysis by criteria category follows.

Ease of application. A five (positive) valence was assigned to this criteria category, based upon a 65 percent relative frequency of occurrence in the 14 units of content coded in this category. Comments, by valence, were:

1. Negative (21%)--The success of the Standard Lottery technique is dependent upon the expert's familiarity with lottery-type betting situations (3:26). A problem in the technique's application is that the expert is unable to discriminate between values when the probability of their occurrence is small (54:97; 58:146).

2. Mixed (14%)--The expert may find it difficult to determine the highest or lowest characteristic value for which he can state a subjective probability (3:27), and

to determine a single probability that makes him indifferent between two lotteries (102:21).

3. Positive (65%)--The Standard Lottery technique is a simplifying device (58:145; 81:477) which is easy to apply (3:27,64). Since probability statements are not made directly, the expert with little probability theory may be more comfortable with this technique (3:36,64; 58:5). The technique also lends itself to solicitation of responses without having to use the personal interview technique (58:145-146).

Adaptability and flexibility. A five (positive) valence was assigned to this category, based upon a relative frequency of occurrence of 75 percent in the four units of content:

1. Negative--None coded.

2. Mixed (25%)--In situations where vagueness is present, the standard lottery technique may prove useful (102:97).

3. Positive (75%)--The standard lottery technique is applicable to virtually any situation involving uncertainties (54:97). Businessmen can find a unique set of weights which describe their attitudes in a more complex situation by using the standard lottery technique (78:14; 79:12). The technique can also be employed to check the consistency of expert responses after another technique was used originally to define the probabilities for the variables of interest.

Reliability and validity. A relative frequency of occurrence of 60 percent resulted in a five (positive) valence for this criteria category, with seven units of content coded. Comments were:

1. Negative (29%)--There is no response consistency check inherent in the technique (3:64; 58:146).

2. Mixed (14%)--The lottery technique should help to reduce vagueness, but it is not possible generally to eliminate it entirely (102:21).

3. Positive (57%)--The internal consistency of lottery techniques can be improved through the use of the lottery procedure (2:16). The lottery results in a more valid density function than direct estimation, providing an improved process for eliciting subjective responses over direct estimation (3:27,36). Considering lotteries also helps to combat vagueness (102:97).

Time. A positive valence of five was given this criteria category, based upon a relative frequency of occurrence of 100 percent in four units of content. Category comments included:

1. Negative--None coded.

2. Mixed--None coded.

3. Positive (100%)--The technique is not time consuming (3:47,64; 58:146), and can be performed without using a time consuming interview (58:145).

Removal of bias. A zero was assigned to this category, since no units of content were coded to this category.

Miscellaneous. A five (positive) valence for this category resulted from a 67 percent relative frequency of occurrence in three units of content. The units of content included:

1. Negative (33%)--Comparing rewards to lotteries reduces decision making to the level of the casino (81:477).

2. Mixed--None coded.

3. Positive (67%)--The technique derives probability density functions through inference rather than direct questioning (3:27); however, only discrete probability functions are derived (58:135).

The Modified Churchman-Ackoff Technique

The evaluation of this technique resulted in a score of seven, based on 14 units of content from two sources. A narrative summarization of the content analysis by criteria category follows.

Ease of application. A one (negative) valence was assigned to this criteria category, based upon a 60 percent relative frequency of occurence in the five units of content coded in this category. Units of content, by valence, were:

1. Negative (60%)--The technique is not as easy to apply as other techniques. To apply it, one must understand the concepts of probability (3:64), and one must use

another technique to establish the endpoints of the distribution (58:154).

2. Mixed--None coded.

3. Positive (40%)--The technique does not require a knowledge of probability theory. Some experts find the technique easier to use for some classes of application than other techniques (58:153).

Adaptability and flexibility. A zero was assigned to this category, since no units of content were coded in this category.

Reliability and validity. A relative frequency of occurrence of 71 percent resulted in a five (positive) valence for this area category, with seven units of content coded. Comments were:

1. Negative (29%)--The technique involves an untested approach (3:43; 58:153).

2. Mixed--None coded.

3. Positive (71%)--The technique offers a systematic method of checking the consistency of relative value judgements made by experts, enhancing the validity of the resulting probability distribution (3:43,64; 58:153).

Time. A negative valence of one was given to this category, based on a relative frequency of occurrence of 100 percent in two units of content. Category comments included:

1. Negative (100%)--The technique is more time consuming than other techniques (3:64; 58:153-154).

2. Mixed--None coded.

3. Positive--None coded.

Removal of bias. A zero was assigned to this category, since no units of content were coded in this area.

Miscellaneous. A zero was assigned to this criteria category, as it also had no units of content.

The Delphi Technique

The evaluation of the Delphi technique resulted in a score of 18, with 497 units of content from 52 sources. A narrative summary of the content analysis by criteria category follows.

Ease of application. A one (negative) valence was assigned to this criteria category, based upon a 76.2 percent frequency of occurrence in the 84 units of content coded in this category. Representative units of content, by valence, were:

1. Negative (76.2%)--A disadvantage of the application of the Delphi technique is that experts are required, and that experts are not easily found and chosen. Difficulties arise in defining rules for the selection and the composition of the panel of experts (12:4,61; 13:38; 28:474; 31:42; 48:182; 56:21; 80:31; 85:53,55). The number of experts must be large enough to assure replicability of results (80:15); however, establishing the required number of reliable experts to assure replicability is difficult (71:22).

When experts are identified within the organization, the problem becomes selection of a panel from among them; when experts are identified outside the organization, the problem of expert identification is much more difficult. The most serious problem in finding a panel of experts is in finding a panel who will not only agree to serve, but who will also be available for a full sequence of questionnaires (63:53). Since there is a tendency for high panel attrition over time (48:182; 75:20), experts may have to be paid to induce them to participate (80:31).

The Delphi technique requires a greater degree of expertise on the part of the analyst than do other techniques (58:160). The success of Delphi is highly dependent on the skill of the analyst-administrator; very few analysts have experience in using the technique (3:62; 80:31). Analyst experience is required in determining what information to feed back to the experts (71:45), in preparing questionnaires (80:16), and in knowing when to stop the iterations (31:26). If the volume of responses overwhelms the analysts, the analysts may have difficulty in digesting and collating what becomes an increasingly formidable amount of material (72:342; 80:32). Responses are difficult to aggregate (58:41), and the aggregation quite expensive if a computer is used (33:132). If there is no meaningful way to aggregate the panel responses, one would probably not want to use the Delphi technique (3:62). Another Delphi major

problem arises in understanding the meaning of the distribution of estimates which have been obtained from the experts (37:70). Translating the information obtained into implementable action plans is a formidable task (13:42). Still another problem is that busy executives often claim that Delphi forecasts and plans are outside the mainstream of their activities, and thus assign Delphi lower priority than immediate problems (13:42).

The Delphi technique requires the use of other techniques to begin the iterative process (58:160), and requires a degree of quantification to be imposed upon subjective judgemental factors. The definition of this quantification is a matter of principal concern to the design team (90:151). In order to use the Delphi, the principles of probability must be understood by the experts (3:64).

There is also a legal difficulty in government agencies using the Delphi technique. An Act of Congress forbids an agency to conduct or sponsor a study in which questionnaires are circulated to more than nine respondents without prior permission of the Office of the Management of the Budget (31:69; 42:55; 80:40).

2. Mixed (12.5%)--The amount of uncertainty that can be tolerated must be considered (37:73). Close cooperation is required between the design team and the intended user (90:151). Planners must match the type of output desired with the alternative outputs which Delphi can produce (37:73).

3. Positive (14.3%)--Delphi does not require participants to meet together, thus allowing a larger number of consultants to be used (58:160; 77:218; 80:27; 85:52; 86:18). The appeal of the technique to potential users is its simplicity, popularity, and directness. The appeal to researchers is Delphi's low cost and relatively painless methodology. A study can be conducted and a paper produced with relatively small effort (75:31,62-63).

Adaptability and flexibility. A five (positive) valence was assigned to this category, based on a relative frequency of occurrence of 75.6 percent in the 45 units of content. Some valence comments were:

1. Negative (13.3%)--The usefulness of Delphi forecasts for corporations is uncertain (37:68), since it is difficult to see what can be done with the "consensus" when at last it is ascertained (68:77). Delphi results provide no means of relating a forecast to the long-range planning of a company (15:176; 48:188). However, Delphi should not be considered for routine decision making (85:55).

2. Mixed (11.1%)--The Delphi procedure has broader potential in the analysis of uncertainty than in the estimation of a group probability density function (58:156). The technique should not be used to predict an unchanging future; it should be used to identify possible futures (83:14). Application of on-line computers and other devices with the technique is not always easy and practical (80:31).

3. Positive (75.6%)--Delphi has been applied to a variety of problems, with versatile application to virtually any area where "experts" can be found (25:6; 58:160; 75:31). Procedures for the conduct of a Delphi exercise are not standard and can be changed to suit the situation. Delphi was listed as the second most utilized technique for long-range studies by industry (25:6). However, Delphi is not limited to forecasting problems. It can also be used to reach final decisions, to arrive at basic analysis inputs, to develop pro and con arguements for political decisions (80:7,27), to stimulate new ideas and alternatives (71:21; 80:30), to evaluate alternative solutions to problems (65:10), to clarify and establish meaningful criteria and objectives, to reduce the number of contingencies, and to communicate before meetings are held (80:27,30). The technique appears to be highly useful in generating preliminary insights into highly unstructured or undeveloped subject areas, leading to greater insight on the target problem (64:10; 75:7). The method can be used to forecast subjective aspects of technologies as well as to generate more objective information (69:10). Delphi may serve to stimulate the experts into taking into account considerations they might have neglected (44:6; 46:2; 47:5-6), and seems to be an indispensible instrument for the technological assessment of research and development projects (28:482). There have already been some useful applications of Delphi in Department of Defense

problems; it is anticipated that in the future Delphi will be employed more frequently in Army systems analyses (80:7-8).

Reliability and validity. A relative frequency of occurrence of 71.3 percent resulted in a one (negative) score for this area category, with 129 units of content coded. Comments included:

1. Negative (71.3%)--Little is known about Delphi's validity, in the sense of yielding more reliable results than rival methods (45:5; 52:39; 75:43,49,67,70; 80:29). Validation of the technique is needed (9:452; 75:65); but may be difficult, if not impossible, to obtain (80:32). The validity of the methodology and data obtained using Delphi have yet to be demonstrated (37:66; 48:186,188; 75:24). The evidence advanced in support of Delphi reliability is less than sufficient (48:180; 56:21) since little research has been done to evaluate the accuracy of Delphi forecasts (63:31; 75:15,70). Acceptance of the accuracy of Delphi is a tacit assumption that has not been clearly explored, either by the rationale of Delphi methodology or by empirical evidence (37:69). Reliability of the Delphi is critically weakened by an absence of recognized administrative standards to guide implementation of the technique (48:184; 75:27,66,69,70). A Delphi prediction of a future event is meaningless if there is no measure of the predictive reliability of the actual occurrence of the event (15:175). Forecasts generated by Delphi are too ambiguous to serve planners (48:188). The

assumption of Delphi that authentic experts exist for predicting the extremely complex events common in Delphi applications may be wishful thinking; Delphi results often represent informed opinion, rather than expert opinion (75:34,35). The quality of the Delphi results is only as good as the quality of the experts (28:474; 33:134). The Delphi technique is an attitude polling technique dealing in "snap" judgements of ill-defined issues, which produce short-lived attitudes about the future which are quite different from systematic predictions of the future (75:38).

2. Mixed (6.2%)--The validity of the Delphi procedure may be considered established in an intuitive sense (45:5). Increased employment of the Delphi in recent years is probably being conducted beyond that which is justified by the controlled experimentation done to date. The assumptions or presumptions that the experimental findings apply to real problems may be questionable (80:28-29). Delphi designers may be accused of ignoring scientific rigor; but they are meeting a demand that cannot be met otherwise, and developing a body of useful knowledge on both good and bad design techniques (88:183).

3. Positive (22.5%)--Delphi is at least as good as, if not better than, other long-range forecasting techniques (64:7; 85:56). A series of experiments with short-range forecasts showed that the Delphi method was superior to conventional methods of business forecasting (63:31).

Delphi procedures usually lead to increased accuracy of group responses (21:vi; 22:1; 76:435). Delphi is more accurate than direct confrontation (85:56), at-large experts (57:20,30), face-to-face committee procedures (57:30; 63:52), and unarticulated intuitive judgements (56:21). Delphi is an excellent method for gathering a group of opinions and forming a general consensus (65:9). The technique provides a systematic and objective analysis procedure for a group of decision makers (24:42; 71:21; 80:30). Proponents of Delphi stress three attributes which contribute to authentic consensus and valid results: anonymity, statistical response, and iterative polling with feedback (75:4).

Time. A negative valence of one was given this criteria category, based on a relative frequency of occurrence of 91.7 percent in 36 units of content. Category comments included:

1. Negative (91.7%)--The Delphi process is quite time-consuming (3:64; 17:420; 33:64; 37:67; 58:41,60; 67:425; 71:46; 80:30). Distribution of the Delphi questionnaires usually takes considerable time (80:30). Getting responses to the questionnaires once they have been sent is also slow (1:30; 31:38; 72:337; 85:55). The extensive number of iterations required in the Delphi also results in a heavy investment of time (1:33; 89:249). As the number of iterations increases, the amount of time necessary to complete the technique increases (15:249; 71:22,46). If the time allotted

is short, the experts may not have time to give Delphi questionnaires adequate attention (3:62; 85:55). If there are long periods of time between sessions, the experts may lose their train of thought or rationale (3:62). Thus, if there is little time available, the Delphi technique may not be a viable alternative (3:62).

2. Mixed--None coded.

3. Positive (8.3%)--The Delphi uses little of the experts' time, compared to other group communication methods (3:62; 85:55; 88:183).

Removal of bias. A five (positive) valence for this criteria category resulted from a 65.1 percent relative frequency of occurrence in 122 units of content. The units of content included:

1. Negative (27.9%)--Delphi can easily slant results in the direction of vested interests, and can produce manipulated convergence of opinion reflecting short-lived attitudes of very small samples of unknown individuals (75:58,63). The form of the Delphi questions may exert too great an influence on the responses (56:21). Since Delphi requires public opinion sampling techniques, it may introduce other kinds of bias. The technique also is vulnerable to selection bias in the selection of experts (48:182), and to the individual biases of analyst-administrators (4:149). If the Delphi questionnaires are prepared by unqualified analysts, the responses to the questionnaires may be biased (3:62) since

each respondent would answer the questionnaire based upon a different set of assumptions (31:21). Experts have a tendency to be conservative when faced with the uncertainties of the future, which allows another bias to be introduced (71:22; 80:32). There exists an uncontrollable and unknown expert halo effect in Delphi, contributing to expert oversell (75:34,41,69). If experts are chosen for subjective or reputational reasons, there is a possibility that the panel will be composed of individuals favorably disposed toward the Delphi, thereby introducing bias (48:182). The artificial shifting of the group's view or generation of an artificial consensus because of dropouts has always been a problem in Delphi exercises (88:182). Delphi asks about event stereotypes, and experts respond with stereotyped estimates (75:50).

2. Mixed (6.5%)--The Delphi procedure is not an absolute guarantee against the degrading influence of the "bandwagon" effect (63:62). Nor is specious persuasion necessarily eliminated by impersonalizing the interaction (4:149). Although pressure for conformity still operates with Delphi, it is an internal and individual pressure (31:27). Individuals may misinterpret the Delphi exercise to be a policy decision tool as opposed to a policy analysis tool; the design team must inform the respondent group of the real intent and purpose of the exercise (90:154). If Delphi is used to determine objectives of an analysis, it

may be undesirable or embarassing to identify the real objectives (80:29). Delphi may serve to stimulate the experts into taking into due account considerations they might inadvertently have neglected, or dismissed as unimportant on first thought (22:6; 46:2; 47:5-6).

3. Positive (65.6%)--Delphi avoids the difficulties and impracticalities of group discussion by avoiding face-to-face confrontation (3:44; 58:41; 64:2); there is no pressure to arrive at a consensus (21:4). Interaction by the group members (experts) is handled in an anonymous fashion (21:5; 57:18; 63:20; 85:336), thus avoiding the possibility of identifying a specific opinion with a particular person (57:17,84; 63:20). This anonymity tends to make the experts less inhibited in their judgements (3:44-45; 12:3; 19:3; 21:16; 63:20; 65:9; 71:22; 80:11; 75:17), and is conducive to independent thought and a more gradual formulation of a considered opinion (64:2). Delphi is designed to overcome the difficulty of an expert unwilling to abandon publicly expressed opinions (4:149; 12:2; 17:419; 42:120; 47:5; 63:20; 67:413; 80:30; 85:51). It is also designed to overcome the "bandwagon" effect of majority opinions (4:149; 17:419; 42:120; 67:413; 80:30; 85:51), and to reduce specious persuasion by the expert(s) with the greatest supposed authority (42:120; 47:5; 57:18; 85:51), or with a domineering personality (69:1; 86:2). The experts can evaluate information strictly on the information's merit,

without being influenced by the personalities and status of the other contributors (13:38; 83:16; 85:56). Delphi eliminates personal antipathy or excessive respect for a particular individual's opinions and individual skill in verbal debate (4:149). Delphi reduces conformity (3:63; 21:16; 80:30) and irrelevant or redundant material (80:30). The reduction in group pressure to conform means that the experts' responses are more likely to reflect their true opinions (58:160). Delphi assures that the opinion of every expert in the group is represented in the final responses (13:37; 21:16), and is designed to call out the kinds of information that each expert feels would enable him to arrive at a confident answer to the question (64:2).

Miscellaneous. A three (mixed) valence was assigned to this category, based on a tie in relative frequency between the one (negative) and five (positive) valences in the 81 units of content. The valences were averaged to give the score of three. Some valence comments were:

1. Negative (45.7%)--After several iterations, the expert may be faced with evaluating projections in areas outside his area of expertise (14:147). Delphi gives the expert who finds himself in the majority a false sense of confidence (28:474; 80:32). The technique has been criticized for its highly normative character which often results from the efforts of the Delphi administrator to obtain consensus or convergence. Convergence is made at the

expense of the extreme opinions which in some instances can be interesting (28:470,474). The Delphi is silent on how much iteration is enough (48:184). Once a Delphi exercise has started, there is no way to guarantee or control for a specified outcome (90:8). With Delphi, it is difficult to take into account the unexpected, and the technique discourages any attempt to reintroduce broader concerns as the studies advance (56:21). Delphi should not be considered when reliable data and time are available (76:168). Delphi pays inadequate attention to psychological values and attitudes toward the future, and as presently practiced, is a psychological projective technique for future "inkblots" (75:29,51).

2. Mixed (8.6%)--The Delphi is not just another polling scheme, and polling practices should not be transferred to Delphi practice without close scrutiny of their applicability (90:157). The Delphi technique has many compelling qualities for lazy investigators, so that there is a danger of a stampede of Delphi "hustlers" forming (77:217).

3. Positive (45.7%)--The Delphi technique creates a well-defined process that can be described quantitatively (21:vi; 56:21; 63:32). Delphi fits into a hierarchal structure of objectives and courses of action. The technique assures that every expert is represented in the final response (57:18), allowing both the majority and minority to have their views presented to the experts as a group (17:420;

63:20-21). The technique forms a consensus of opinion by requiring justification for any significant deviation from the group average (85:52). Extreme responses may be even more useful to management than those of the majority (80:27). The results of a Delphi exercise are subject to greater acceptance on the part of the group than are the consensuses arrived at by more direct forms of interaction. Delphi stimulates thinking and involves management in the forecasting process. This by itself could well be enough to justify its use (37:74).

The DeGroot Consensus Method

This relatively new method received a score of seven based on six units of content from two sources. Units of content are summarized below.

Ease of application. This category received a five (positive) valence, since all of the units of content had a five valence. Comments included: the method is intuitively appealing (27:118); the simplicity of the procedure has much to recommend it (49:283); the method presents simple conditions for determining whether it is possible for a group to reach a consensus; and when consensus can be reached, the weights to be used in the consensus which can be explicitly and simply calculated (27:118).

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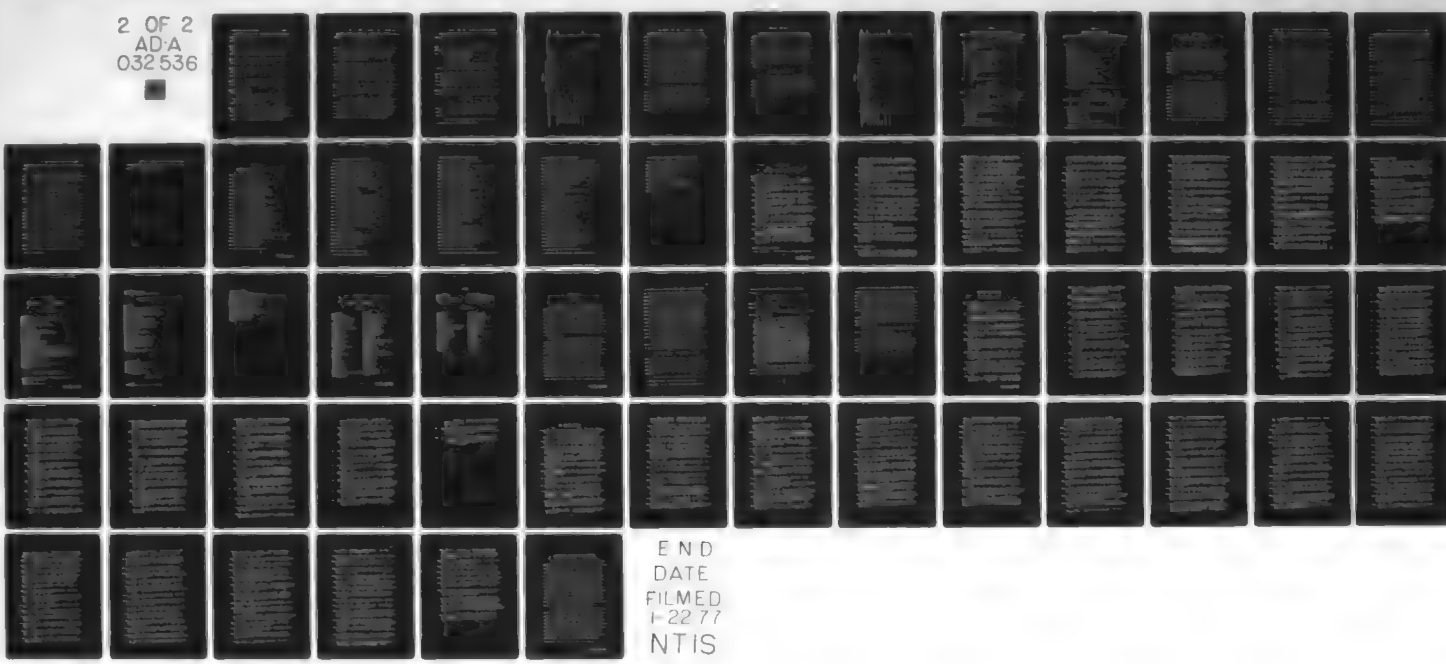

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Adaptability and flexibility. The one unit of content in this category was coded one (negative), and stated that the postulated form of the revised distributions may be too restrictive (49:283).

Reliability and validity. The one unit of content in this category was coded one (negative). The comment was that the method had not yet been empirically tested (49:283).

Time. This category received a score of zero; no units of content were coded in this category.

Removal of bias. A score of zero was assigned for this criteria category, since no units of content were coded in the category.

Miscellaneous. This category also received a score of zero as no units of content were coded in the category.

The Direct Estimation Technique

The evaluation of this technique resulted in a score of 13, based upon 20 units of content from five sources. A narrative summarization follows.

Ease of application. A five (positive) valence was assigned to this criteria category, based on a relative frequency of occurrence of 71 percent in the seven units of content in the category. Representative comments by valence were:

1. Negative (29%)--The expert must be knowledgeable in probability theory (58:161). People often require training before they accept the technique (55:24).

2. Mixed--None coded.

3. Positive (71%)--This technique is simple in application (3:24; 55:25; 87:45). Direct Estimation does not require another individual to interview the expert (58:161), and a probability distribution can be generated without burdensome calculations (55:25).

Adaptability and flexibility. A one (negative) valence was assigned to this category, based upon a one valence coded to the one unit of content, which stated that situations in which direct estimation seemed least satisfying were those concerning rare, unusual, or unheard of instances (10-B433).

Reliability and validity. A relative frequency of occurrence of 67 percent resulted in a one (negative) valence for this one category, with six units of content coded. Comments were:

1. Negative (67%)--This technique has little likelihood of success in most cases (3:24); its validity has been questioned (55:24). Direct estimation is least likely to work because individuals do no think directly in terms of probabilities (87:45). Also, the technique does not check on the consistency of the responses (58:161).

2. Mixed (33%)--This technique probably produces the least valid responses (55:162), but may be a good technique (10:B-433).

3. Positive--None coded.

Time. A positive valence of five was given this criteria category, since all of the five units of content were coded five. Category comments included:

1. Negative--None coded.

2. Mixed--None coded.

3. Positive (100%)--Direct estimation takes place very quickly (10:B-428,B-433; 55:25; 58:161).

Removal of bias. A five (positive) valence was assigned to this category, since the one unit of content was coded five. The comment was that there is no possibility that the interviewer will impose his bias on the responses (55:161).

Miscellaneous. A score of zero was assigned to this category, since there were no units of content coded to the category.

CONCLUSIONS

As can be seen in Table 10, the Standard Lottery technique received the highest evaluation score of 24, thus answering the research question and meeting the research objective.

The researchers believe that these results are inconclusive, for the following reasons:

TABLE 10

Summary of Content Analysis

Technique	Number of Sources	Number of Units of Content	Score
Choice-Between-Gambles	9	57	16
Standard Lottery	9	33	24
Modified Churchman-Ackoff	2	14	7
Delphi	52	497	16
DeGroot Consensus	2	6	7
Direct Estimation	5	20	13

1. The sample size, both in number of sources and in number of units of content, was highly variable; the number of sources ranged from two for the DeGroot Consensus technique to 52 for the Delphi technique, with units of content varying in number from six for the DeGroot method to 497 for the Delphi technique. When using content analysis, with resulting data of face validity, the researcher needs as many sources of data as possible in order to obtain conclusive results. This proved difficult to do in the field of subjective probability assessment. The only technique that had a large number of sources was the Delphi, with 52 sources. The Standard Lottery, with nine sources, was a distant second to the Delphi. Thus, in order to make valid comparisons between the assessment techniques, more sources of data would be required for techniques other than the Delphi.

2. Several of the techniques had not been empirically tested to a great degree. This greatly affected the number of sources available to the research team. More field testing of the assessment techniques is required before stronger conclusions can be drawn as to whether the Standard Lottery is the technique best suited for subjective probability assessment.

COROLLARY CONCLUSION 1

All of the units of content were summarized by criteria category to find which criteria categories were mentioned most frequently in the critical literature, and therefore, which categories were of the most interest to users/researchers. As shown in Table 11, reliability and validity ranked first, followed by ease of application, removal of bias, adaptability and flexibility, and time. Thus, users are more interested in the "goodness" of an assessment technique than in range of application or speed of results.

COROLLARY CONCLUSION 2

Each criteria category was also surveyed to find the sub-areas within each category which were mentioned most often in the units of content; for example, expert training required was one sub-area in the ease of application criteria category. These sub-areas, and their frequency of occurrence, are shown in Tables 12 through 15.

TABLE 11

Units of Content Summary

Criteria Category	Gambles	Lottery	C/A	Delphi	DeGroot	Direct	Total
Ease of Application	17	14	5	84	4	7	131
Adaptability/Flexibility	4	5	0	45	1	1	56
Reliability/Validity	23	7	7	129	1	6	173
Time	4	4	2	36	0	5	51
Removal of Bias	6	0	0	122	0	1	129

TABLE 12

Ease of Application Criteria Category

Sub-Areas	Number of Units of Content
Ease of Use/Administration	28
Simplicity	13
Expert Selection/Definition/Motivation	28
Number of Experts/Analysts Required	8
Expert Training/Skills Required	23
Analysts Skills Required	18
Acceptance of Technique by Analysts/Experts	4
Workload/Attrition of Experts	5
Cost of Use	3

TABLE 13

Adaptability and Flexibility Criteria Category

Sub-Areas	Number of Units of Content
Application to a Variety of Situations	17
Potential Usefulness	5
Comparative Utilization/Frequency of Employment	2
Limitations	2
Flexibility of Procedures	2
Usefulness of Specific Applications	28

TABLE 14

Reliability and Validity
Criteria Category

Sub-Areas	Number of Units of Content
Method Validity	52
Data/Results Validity	29
Ease of Validation/Evidence of Validity	4
Accuracy/Precision of Results	19
Vagueness of Results/Method/Data	13
Reliability/Evidence of Reliability	6
Consistency of Responses	9
Objectivity of Results/Data	6
Goodness of Experts/Respondents	13
Relative Effectiveness Compared to Other Techniques	18

TABLE 15

Time and Removal of Bias
Criteria Categories

Sub-Areas	Number of Units of Content
Time Required for Application of Technique	50
Analyst/Expert Bias	37
Method/Procedure Bias	12
Conformity/Forced Consensus Effect	23
Status Bias/Personality Dominance Effects	14

Chapter 5

RECOMMENDATIONS FOR FURTHER RESEARCH

GENERAL

Vague areas still exist in both the behavioral and statistical aspects of subjective probability assessment. Empirical testing of assessment techniques has been fragmentary. Below are some specific recommendations for further research in order to broaden the base of practical knowledge concerning subjective probability assessment techniques.

RESEARCH RECOMMENDATIONS

1. Follow-on research in the actual application of the different subjective probability assessment techniques would be useful in comparing their effectiveness and utility. Subjective judgement, through the application of the techniques, would be made explicit, providing feedback on the techniques and therefore an impetus to the validation and improvement of the techniques in general. In a very real sense, a "laboratory" that is suitable for testing these techniques is a weapon system source selection. The techniques have little utility unless they can be applied to such long-term processes as source selection which are

characterized by the sequential accumulation and assessment of information. An ASD source selection is recommended as such a "laboratory." The recommended sequence of events is as follows:

a. The research team, in conjunction with the USAF Business Research Management Center (BRMC) and the Aeronautical Systems Division (ASD), would identify a weapon system source selection completed within the previous six months, and also identify 15 to 20 individuals who served as evaluators on the associated Source Selection Evaluation Board (SSEB). Permission would first be obtained through the BRMC from the Source Selection Authority to allow the source selection to be used as the "test bed," and to make appropriate source-selection documents available to the research team. Permission would next be obtained, also through the BRMC, from the supervisors of the identified evaluators in order to allow their participation in the research effort as subjective probability estimators.

b. The researchers would ascertain risk areas identified during the source selection, using the source-selection documents.

c. To the extent possible, the research team would provide the estimators with tutoring in the concepts of subjective probability, to insure that each estimator had an understanding sufficient to apply the technique. Records would be kept of how much training was required, for later use in evaluating the techniques.

d. Using each subjective probability assessment technique, the research team would elicit subjective probability distributions for each identified risk area. Five to seven estimators would be randomly selected from the total estimator group for the application of each technique. For techniques in which group consensuses are not reached, an average of each estimator's subjective probability for the associated risk area would be used to aggregate the estimators' responses for that risk area.

e. The resulting assessment of uncertainty would be quantified, using the Martin Cost Model (see Appendix E), into the expected final cost for the selected weapon system.

f. To ascertain the behavioral aspects of each subjective probability technique, each estimator would, upon completion of his estimation for an individual technique, answer a questionnaire containing the following questions:

(1) Will introduction of the subjective probability technique into the source-selection process serve to clarify, to confuse, or to have no noticeable impact upon the estimator's subjective probabilities?

(2) Will introduction of the technique increase, decrease, or have no noticeable impact upon an estimator's confidence in the accuracy of his indicated subjective probabilities?

(3) Will introduction of the technique increase, decrease, or have no noticeable impact upon the number of subjective probability discriminations made?

(4) How satisfied would an estimator be with whatever assessment structure emerged from introduction of the technique?

(5) To what extent would the estimator regard the clarification, confidence, or satisfaction obtained from the technique as worth the additional time and effort (marginal cost) in applying the technique?

(6) To what extent would the estimator utilize the technique in other decision situations?

g. The future cost estimates obtained from the Martin Cost Model would be used to validate each technique, when compared with the actual final cost of the weapon system.

2. There is a great need for research in the area of how people evaluate or assess uncertainty in a descriptive sense; that is, in day-to-day activities, instead of just people performing under university test conditions. It is difficult to infer how good (or bad) decisions are made from experiments with university test subjects. "Real-world" situations should be sought out for research.

3. Research needs to be done into what the subjective assessment task means to the assessor in terms of his attitudes and motivation toward assessment.

4. Research is needed into the amount of training that individuals with varying degrees of statistical sophistication need to obtain a working knowledge of subjective probability assessment.

5. Finally, research would be useful in the area of the attitudes of experienced decision makers toward subjective probability assessment and its uses.

APPENDIX A

WEAPON SYSTEM PROGRAM UNCERTAINTIES

National Objectives and Strategies

Present Defense Systems Capabilities

Defined Threat or Proposed Change/Innovation

Current/Future State of Technology

Fiscal Information/Available Resources

Desired Date for Operational Capability

Expected Operational Environment

Mission Responsibility Assignment/Harmonization

Mission Objectives and Priorities

System Operational/Functional Requirements

Performance Envelopes/Design Constraints

Necessary Technology Advance and Risk Assessment

Estimated Program Costs Schedules/Concurrency

Program Approval and Budget Authorization

Rudimentary Development Plane and Objectives

System Performance/Design Requirements

Initial Specification Tree Subsystem Interface Definition

End Item Performance/Design Requirements

Maintenance and Logistics Plans

Test and Evaluation Concepts

Training and Personnel Requirements

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Realistic Program Costs and Schedules

Program Management/Development/High Risk Areas

Long Lead Parts, Tooling and Facilities

Applicable Specifications/Waivers

Feasible Design Approach for End Items

Preliminary Drawings for Modules/Units

Reliability/Maintainability Budgets for End Items

Critical Components/Design Areas Identified

Subsystem Specifications

End Item Interfaces Defined

Preliminary Operational Facilities Criteria

Test Facility/Range or Support Agency Requirements

Identified/Approved Engineering Design Changes

End Item Configuration and Acceptance Requirements

Detailed Design and Assembly Drawings

Circuit Diagrams, Mechanical/Packaging Layouts

Quality Assurance and Test Requirements

Estimated Production Rates/Quantities/Deliveries

Process Specifications and Standards

Make or Buy Decisions

Configuration Control Plans

Long Lead Parts/Materials/Tooling Quantities

Parts Lists, Components Space

Needed On-Dock Delivery Dates

Purchase Authorizations

Material Sources and Market Prices

Permissable Substitution Parts Lists

Receiving and Inspection Instructions

Preliminary Design and Assemble Drawings

Shop Fabrication Instructions

Required Materials and Parts

Test Objectives, Environment, Expected Results

Detailed Test Plans and Procedures

Test Facility, Support Equipment, Instrumentation

Known Configuration of Test Hardware

Test Measurements, Data, Variables, Parameters

Report Documentation Required

Production Line/Material Handling Layouts

Tooling Design Jigs and Fixtures

Production Facilities and Factory Test Equipment

Materials and Parts Inventory On-Hand

Routing, Scheduling and Dispatch Orders

Production Procedures, Plans and Processes

Realistic Cost and Delivery Schedules

Subcontractor Conformance Space

Inspection Tolerances

End Item Acceptance Test Requirements

Test Objectives, Extreme Environment Conditions

Acceptable Quantity/Time Duration Sample Sized

Test Measurements, Data, Variables, Parameters

Data Reduction and Analysis Procedures

Report Documentation Requirements

Test Objectives, Environment Defined

Acceptable Demonstration Criteria Per System Specifications

Detailed Test Plans and Procedures

Test Measurements, Data, Variables and Parameters

Test Site, Support Equipment, Instrumentation

Support from Range/Other Contractors/Agencies

Production Hardware Including Necessary Spares

Other Required System Segments/Elements

Data Reduction and Analysis Procedure

Report Documentation Requirements

Training Course Materials

Required Training Equipment and Facilities

Qualified Instructors

Field Requirements for Trained Personnel

Scheduled Number of Students

Examination for Minimum Acceptable Skill Level

Percentage Expected to Attain Achievement Level

Shipping and Transportation Plans

Receival Inspection Procedures

Operation Facilities Constructed

Support Facilities/Equipment on Hand

Installation, Assemble, Check Out Procedures

Equipment Scheduled Delivery Dates

Realistic Costs and Schedules to Completion

System Performance Demonstration Plans

Operation Plans, Instructions, and Manuals

Maintenance and Logistics Plans

Personnel Subsystem Evaluation Plans

Reliability, Maintainability, Evaluation Criteria

User Performance Capability Evaluation Criteria

Required Data and Reports on System Performance

Data Reduction/Analysis Techniques Responsibility

System Acceptance and Turnover Agreement

Transition of Logistic Support Responsibility

Preliminary Follow-On Plans

Recommended Changes to System Design

Inputs for Next-Generation System Concept

Program-Completion Objectives Accomplished

Human Engineering

APPENDIX B

CONTENT ANALYSIS SOURCE LISTING

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APPENDIX C

PHRASES USED TO CODE UNITS OF CONTENT TO EACH CRITERIA CATEGORY

EASE OF APPLICATION

Acceptance
Aggregation of group response
Amount of material experts/analysts must process
Application of computers
Attrition
Communications between experts
Cost
Cumbersomeness
Ease of determining values
Ease of use/Application/technique
Expert availability
Expert composition
Expert inducements
Expert selection
Expert training required
Knowledge of probability
Legal ramifications
Necessary skills to administer/interview/measure
Necessary skills to analyze results
Necessary skills to prepare questionnaires
Necessity of soliciting cooperation from experts
Necessity to meet at a common time, common location
Necessity of using personal interview
Number of calculations
Number of experts required
Simpleness
Use in conjunction with another technique
Use of value type questions
Workload

ADAPTABILITY AND FLEXIBILITY

Application to a variety of problems/situations
Comparative utilization
Flexibility
Frequency of employment

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Limitations
Potential usefulness
Usefulness of specific application

RELIABILITY AND VALIDITY

Accuracy
Ambiguity
Application to real world problems
Check on consistency of responses
Comparative goodness of prediction
Comparison of relative effectiveness
Data validity
Ease of validation
Establishment of reliability
Goodness of experts
Internal consistency of results
Knowledge of validity
Likelihood of success/working
Method validity
Objectivity
Objectivity of analysts
Precision
Reasonableness
Representativeness of experts
Statistical significance
Stereotypeness of thinking
Sufficiency of reliability
Suitability for evaluation
Tested
Vagueness
Validity of probability function

TIME

Length of time
Length of time between iterations
Time allowed
Time comparison to other techniques
Time estimated
Time factor
Time required/consumed

REMOVAL OF BIAS

Anonymity
Antipathy for individual's opinions

Bandwagon effect
Bias of questionnaires
Committments to earlier statements
Comparison to psychological difficulties of groups
Conformity
Effects of dominant individual
Ego involvement
Elimination of group conflicts
Expert selection bias
Face to face confrontation
Halo effect
Individual analyst/expert bias
Influence of individual expert personalities
Introduction of bias
Personality dominance
Specious persuasion
Statue

APPENDIX D

PHRASES USED TO CODE UNITS OF CONTENT TO EACH VALENCE CATEGORY

NEGATIVE

Ambiguous
Amorphous
Can be negated by
Conducted beyond that which is justified
Cannot be sustained
Caution
Could not be used to
Critical step involves
Criticized
Dependent on
Difficult
Difficulties in
Disadvantage
Distortion
Does not allow
Drawback
Embarrassing
Exerts too great an influence
Expensive
Forbids
Formidable task
Hazard
Ignores
Impairs
Impossible
Impractical
Inhibits
Is critical
Lack of
Major problem
Makes much more complicated
Misinterprets
Misunderstand
Misused
Must be available for use
Must be careful
Must understand
No means of relating
Not easy
Not explicit
Not inherent in
Not recommended
Not satisfactory
Not substitute for
Not sufficient
Not viable
Overstated
Overwhelms
Plenty of should be allowed
Presents a problem
Prohibits
Questionable
Rarely shown
Requires
Should be at least
Should not be considered for
Specious
Stereotyped
Unable to
Uncertain
Undesirable
Unproven
Untenable
Untested
Untrustworthy
Usually fails
Vague

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MIXED

Is probably
May
May be
Not absolute guarantee against
Not always
Not an absolute
Not generally possible
Not necessarily
Potentially useful

POSITIVE

Adjusts well to
Advantage
Aids
Applicable
Appropriate for
Assures that
Avoids
Avoids the disadvantages
Avoids the possibility
Can be changed
Can be used to
Conducive to
Does not require
Easier to use
Efficient
Eliminates
Encourages
Excellent
Fits into
Free from
Good
Helps to
Less subject to
Lends itself to
Major attraction of
Minimizes
More accurate
Much easier to
Not limited to
Not skewed by
Overcomes
Provides
Provides sounder basis
Reduces
Refines
Removes
Superior to
True
Useful
Uses little of
Versatile
Well defined

APPENDIX E

THE MARTIN COST MODEL

The Martin Cost Model is a conceptual model for negotiated sole-source development contracts formulated by M. D. Martin in his doctoral work at the University of Oklahoma. The model uses the parameters of time, uncertainty, information, and their interactions, to illustrate the relationship between development program costs and the disorder present in the program at contract award, and to predict the final cost of a development program at the time of contract award.

Time is taken as the underlying parameter used to relate the other three parameters (61:117). As a decision maker looks farther ahead in time in making decisions, uncertainty about the outcome of a situation increases (61:49). Risk and uncertainty can be equated in the decision process. Risk is usually thought of in terms of the possibility of a future event occurring, based on an objective probability distribution. Uncertainty is generally defined as that situation where no such objective distribution exists, with little or no useable information present. A decision maker faced with uncertainty, where a decision is required, makes a subjective probability

assessment as to future outcomes based on his experience and intuitive "feel" for the situation, thus treating uncertainty in the same manner as risk (61:37-38). Uncertainty at a certain point in the time continuum is inversely proportional to the amount of information present at that point. Martin distinguished between the amount and the usefulness, or efficacy, of information, and stated that the efficacy of information received from a management information system was the most important variable in the information-uncertainty relationship (61:117). A certain cost to the decision maker will be associated with more information/informational efficacy about a specific situation. Program costs will also increase directly with increases in uncertainty of program outcomes (61:117).

Martin uses the communication system theory of Shannon and Weaver to relate the uncertainty in a system to the entropy, or disorder, present in a system (61:122):

$$H = \Sigma\, p_i \log p_i \qquad i = 1, 2, 3, \ldots, n$$

where H equals entropy, and $p_1, p_2, \ldots, p_n$ are the individual probabilities of choice for certain outcomes of the system. Thus the more choices that are available in a system, the more the disorder, or entropy, present in the system.

It is possible to increase the order in a closed information system, thus decreasing the entropy (negentropy). In an information system, entropy can be

related to informational efficacy by the equations (61:121-22):

$$H + IE = 1; \quad IE = 1 - H$$

where IE equals informational efficacy, or order, and H equals entropy, or disorder.

Martin made the following assumptions in formulating the model (61:125-26):

1. The theory is normative rather than descriptive.
2. The effective cost for a program can be represented by a ratio of target costs to the informational efficacy of the data in a closed decision-making system.
3. Perfectly competitive markets exist. Contracts are let on a competitively negotiated basis. This assumption will be relaxed subsequently.
4. Entropy is the measure of the information or disorder in a system; whereas, negentropy is a measure of the order in a system and can be equated with informational efficacy.
5. The informational efficacy varies inversely with the number of choices or possible events which can occur as related to the decision-making system. If one course of action seems almost certain, then informational efficacy is increased and vice versa.
6. Since contract price usually includes an amount for profit, this fact must be considered. Ecomonic cost includes the profit factor, and can, therefore, represent contract price.
7. No limitations on funding exist. Programs can be fully funded in anticipation of a possible cost growth.

Using these assumptions, the expected cost including profit, or economic cost C_E, can be related to the initial cost estimate C_I through the equation (61:126):

$$C_E = \frac{C_I}{IE}$$

One can see if IE equals one, or certainty exists about the contract outcome, C_E equals C_I, and no error exists between estimated and final costs. Thus the amount of informational usefulness present in a weapon system development program can be used by a program manager at contract award time to estimate cost growth for the program, or decide on the need for more information before awarding the contract.

Martin demonstrated the logical consistency of the model in his dissertation (61:146-47), and the model was used by two AFIT thesis teams with the following limitations (38:35-36; 5:66-67):

1. The model was developed for application to weapon system development programs.

2. The model is limited by the quality of information subsystems in the overall program system; if information systems cannot identify all possible alternatives at a given point in time, an accurate measure of uncertainty is not possible.

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